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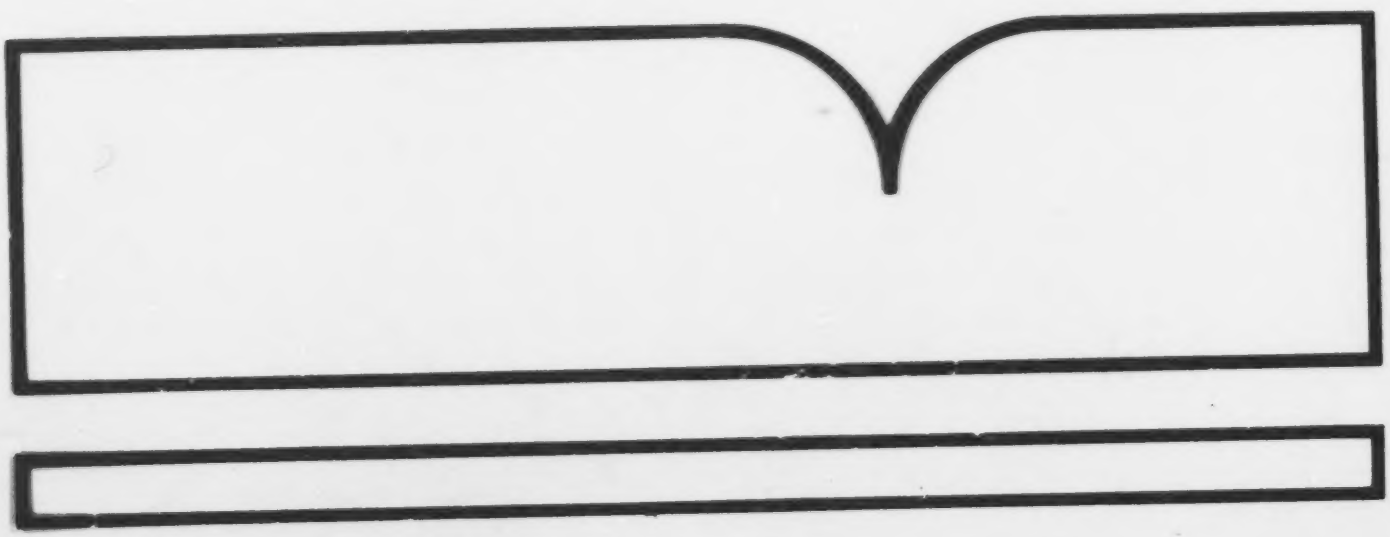

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Recommendation for future research are given.

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SUMMARY OF THE WORKSHOP ON THE EFFECTS OF AIR POLLUTANTS ON REGIONAL CLIMATE

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EXECUTIVE SUMMARY

It has been known for more than half-century that the amount of sunlight arriving at the earth's surface under cloudless skies is governed by the intervening atmospheric haze. However, a quantification of the magnitude of the depletion and an estimate of its geographical extent in North America were only recently published by Ball and Robinson (1982). Their conclusion for the central United States that the annual average depletion is 7.5% was the impetus for workshop to discuss the environmental consequences of this effect of aerosol particles. Here, the depletion is quantified in terms of a loss of irradiance, which is defined as the total solar energy reaching the earth's surface per unit of time.

In the opinion of numerous meteorologists, agronomists, and atmospheric chemists, this estimated reduction is impressively large. The redistribution of such significant amount of solar energy in the lower troposphere should produce observable and measurable meteorological effects. These should in turn lead to changes in surface temperature, and might lead to agricultural effects as well. The question then arises as to the magnitude of the meteorological, surface, and agricultural effects, none of which as yet been observed or quantified.

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properties of the haze quantitatively confirm the estimate of 7%. This workshop also confirmed that the geographical extent of loss of irradiance is roughly from the Mississippi River to the Atlantic coast and from Tennessee to southeastern Canada. This region is about 1000 km across and has an area of about 10^6 km^2.

Among the meteorological effects expected from regional haze is a shift in the temperature profile near the earth's surface, with cooler air near the ground leading to increased static stability. The surface temperatures should decrease, while temperatures aloft within the hazy layer may increase. Besides decreased and evaporation at the surface, convective activity and cloud formation may decrease. Alternatively, heating aloft may move convective activity upward and change the height of clouds. The occurrence of rain and the amount of rain could be affected, but not predictably.

The decreased heating of the surface itself should lead to lower soil temperatures and less evapotranspiration. Consequent response of vegetation include lowered plant temperatures, less heat stress, later planting dates, and perhaps shorter growing seasons (all dependent on location and crop). It is very difficult to know what the overall consequences might be for annual crops and literally impossible to predict the result for perennial crops (e.g., forests). The consensus of the workshop was that aerosol-caused reduction of irradiance would likely result in a delay of the start of the growing season and a shortening of its length by about one week, depending on the level of haze.

It was agreed that further research is warranted in order to better understand these potentially important effects. Four main points emerged:

1. It is necessary to establish the relationships of the decreased irradiance to the sources of the aerosols, both natural and man-made.
2. Monitoring of solar irradiance and of the relevant optical properties of aerosols is needed and should be continued for at lease a decade to document natural variability and trends.
3. In general, the meteorological effects need to be understood and quantified. Substantial basic research on the physics of the boundary layer is warranted.
4. Although it is not possible to enter into all facets of the agricultural effects until the meteorological effects are established, it is clear that the agricultural consequences for both annual and perennial crops demand attention and research

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND PURPOSE

This workshop was convened by the Environmental Sciences Research Laboratory of the U.S. Environmental Protection Agency (EPA) Office of Research and Development to consider the influence of aerosols on regional climate.[1] Aerosols have been implicated in climate change by several earlier investigators (Bryson, 1968; Ensor et al., 1971); however, the magnitude or even the sign of the effect remained to be determined. A paper by Ball and Robinson (1982) estimated that the likely effects of aerosols would be (1) cooling of the ground by reduction of the direct solar radiation flux by backscattering and (2) warming of the atmosphere in the planetary boundary layer[2] by absorption of sunlight. Additionally, Twomey (1976) suggested that carbon aerosols in clouds could have significant effects on the earth's radiation balance. This workshop, composed of a multidisciplinary panel of experts in the fields of meteorology, atmospheric chemistry, air pollution, cloud physics, radiative transfer in the boundry layer, microscale meteorology, forestry, and economics, was convened to provide a timely review of this subject.

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[1] Aerosol is defined as a stable dispersion of liquid or solid particles in a gas. Although the term aerosol includes both the gas phase and the particulate phase, it is frequently used to refer to particles only. Regional climate is defined as the synthesis of all meteorological or weather-related elements of the environment considered on a continental or subcontinental scale rather than on a global scale.

[2] The boundary layer or planetary boundary layer is defined as that part of the atmosphere just above the ground that is well-mixed throughout its vertical extent during the daytime. Its extent is 1000 to 200 meters.

Several questions were posed: What are the potential effects of aerosols on regional climate? Are these effects of sufficient magnitude and significance to justify further consideration by the EPA? If so, what are the key scientific issues and research needs?

1.2 SUMMARY OF FINDINGS

1.2.1 Potential Effects

The participants at the workshop agreed that the presence of aerosols in the mixing layer leads to a number of perturbations in the radiative energy balance. The aerosol layer over a large part of the eastern United States is estimated to cause an average annual loss of approximately 7% of the solar energy that would otherwise reach the ground. The total solar energy reaching the earth's surface per unit of time (e.g. watts/m^2) is called irradiance and includes both direct solar radiation and sunlight that is scattered toward the ground by particles and gases in the atmosphere. Ball and Robinson (1982) estimated that about half of the 7% is lost by backscatter to space and the other half is absorbed within the boundary layer. This leads to a redistribution of heating in that part of the boundary layer containing aerosol, with less heating of the ground and more heating of the air in the aerosol-containing boundary layer. Heat loss, through emission of long-wavelength radiation by aerosols,

may or may not balance energy absorption in the visible wavelengths. If one process dominates the other, the aerosol may lead to either a net cooling or a net heating of the boundary layer.

The area that experiences this loss of solar irradiance is approximately 1000 km (about 600 mi), in horizontal extent covering an area of approximately 10^6 km^2. The region of the country in which this meandering hazy air mass -- called a "haze blob" -- may be found ranges from the Mississippi River to east of the Atlantic coastal states and south of Tennessee to the upper portions of the Great Lakes region and southeastern Canada. Figure 1 illustrates this horizontal extent as evidenced by measured turbidity.

Substantial amounts of data as well as theoretical calculations demonstrate that the optical effects of this haze blob are substantially controlled by sulfate and soot-containing aerosol. Figure 2 is a map of sulfate aerosol concentration; it has almost the same geographic extent as the area of high turbidity shown in Figure 1.

Aerosols may also influence the optical properties and microphysics of clouds. The increased number of cloud nuclei should result in an increased albedo (The fraction of received solar radiation reflected back to space and therefore lost to the earth-atmosphere system). Carbon particles are present in rain, snow, and ice, and are therefore expected to be in cloud droplets. The presence of carbon should lead to a decrease in albedo. Aerosol particles of other chemical composition (such as sulfates, nitrates, and organics) could also lead to a modification of cloud processes.

1.2.2 Significance of Effects

Although it is clear that pollution aerosol causes sizable perturbations to the radiative energy balance on a regional scale, it is not clear that these perturbations cause significant effects, either detrimental or beneficial. It is of scientific interest to study the sources and effects of the changes and to improve our understanding of atmospheric processes. However, the potential for significant environmental effects is so large that the EPA is justified in undertaking further analysis to better define the likelihood and extent of

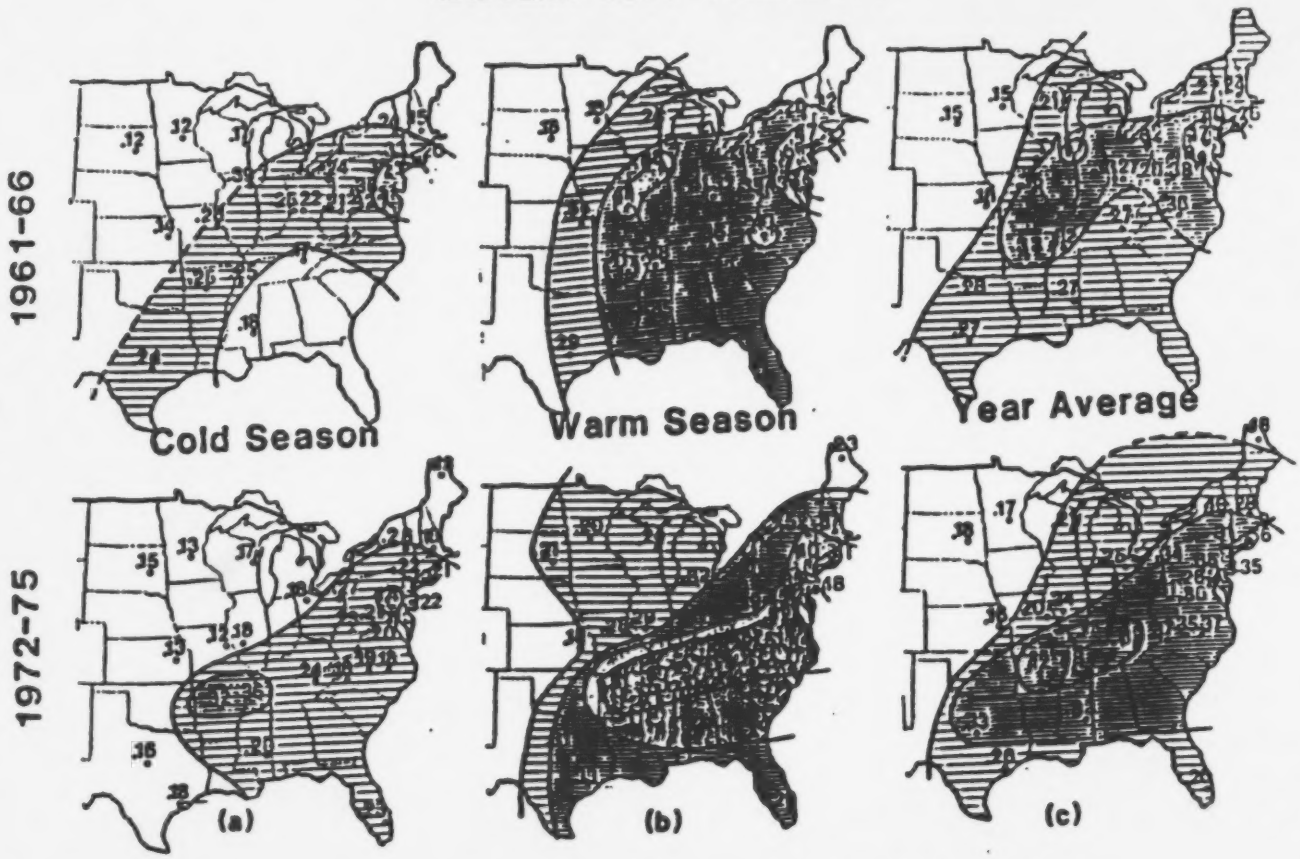

Fig 1. Spatial distribution of haze vertical optical depth at 0.5 um in 1961-66 (top row) and 1972-75 (bottom row) from 26 sites. (a) Cold season, October-March, (b) Warm season, April-September, (c) Yearly average.

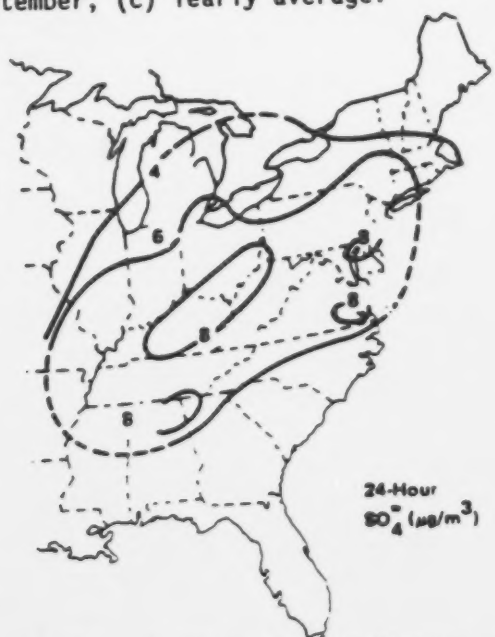

Fig 2. Composite spatial distribution of 24-hour average concentrations of sulfate ($\mu g/m^3$) from one representative month in each season between 1977 and 1978. This average is approximately equivalent to an annual average.

detrimental effects. Neither the effects of changes in cloud albedo nor the ratio between energy absorption and energy loss by backscattering and emission are known well enough to allow prediction of whether aerosols will cause atmospheric heating or cooling. However, the aerosols will cause atmospheric heating or cooling. However, the aerosol effects will either increase or decrease regional-scale atmospheric heating the same extent (order of magnitude) as the carbon dioxide (CO_2) greenhouse effect. Changes in particle concentration and type due to control measures and changes in industrial activity and transportation could also alter the magnitude and direction of these effects. It is clear that (1) the loss of irradiance is about 7%, and (2) this should be large enough to cause observable effects on regional-scale climate.

Although the annual average loss of energy at the ground over the eastern United States is estimated to be about 7%, episodic occurrences of the haze blob or large meandering masses of polluted air during spring, summer, and fall can cause two to three times this loss. This very large reduction in energy supply may have significant effects on biological productivity (agronomic and forest crops). For those crops in which photosynthesis does not become light-saturated, the potential exists for a direct reduction in productivity in relation to the reduction in solar radiation.

A reduction in surface solar energy supply also reduces the energy-using processes of evapotranspiration, surface air heating, and soil heating. Resultant surface air and soil temperature reductions may also have a direct effect on agricultural and forest production. For many plants, biological production is directly proportional to the sum of mean daily temperatures (above

a threshold value) during the growing season. Thus, even small reductions in daily temperature values, accumulated over the growing season, have the potential for significant reductions in crop production. However, at the current stage of scientific understanding of this phenomenon, it is not possible to provide even a crude quantitative estimate of the effects.

The potential reductions in surface air and soil temperature may also delay the initiation of the growing season. This effect could be magnified when the occurrence of a radiation-reducing haze blob coincides with long winters, i.e., late spring conditions. Under these situations, soil thawing and soil and air warming may be significantly delayed. The associated delay in planting dates and the start of the growing season would produce a reduction in the length of the growing season, which could significantly reduce crop production or require choosing alternative cultivars with attendant costs and loss of production. Several day-to week-long haze episodes, reducing solar radiation 10% to 15%, are known to occur during April and May approximately once every ten years in the United States.

One counteracting effect is the potential reduction in evapotranspiration. If the reduction in evapotranspiration occurred during midsummer, with high temperature and reduced soil moisture conditions, it could reduce the potential water stress effects on crop production.

It is possible that some of these haze blobs could travel northward into Canada, causing similar growing season delays during late spring. The international complications could be comparable to those of acid rain.

1.2.3 Scientific Issues and Research Needs

It is important to point out that the research related to the regional-scale climatic effects of aerosols is but one of a class of research topics concerning the atmospheric properties and behavior of this group of trace atmospheric substances. As such, studies of regional-scale climatic effects cannot be meaningfully isolated from a broader understanding of the causes and consequences of atmospheric pollution. The workshop therefore cautioned against the development of programs that are separated from topics such as visibility, cloud physics and chemistry, and boundary layer/cloud process interactions. To utilize the existing relevant talent in the United States and to provide this necessary broad view, it is especially important to encourage the aerosol research community to undertake studies of these regional-scale effects and their causes.

The following two chapters explore (1) concerns in the scientific community at this time and (2) specific research needed to quantify and understand potential consequences of aerosols on regional-scale climate. The appendix contains abstracts of the scientific contributions of individual investigators.

CONCERNS OF THE SCIENTIFIC COMMUNITY

The workshop participants discussed a wide range of scientifically-important questions relating to aerosol-induced climate alterations. Significant and potentially undesirable effects of the air pollution aerosol direct effects on climate, influence on clouds, and impact on agriculture. These effects are discussed separately in the following subsections.

2.1 THE DIRECT INFLUENCE OF AEROSOLS ON CLIMATE

There are a number of compelling reasons for recognizing the importance of a range of regional climatic effects of aerosols. The rationale that follows is based on a hierarchy of observed effects, ranging from those that are directly measured and can be quantitatively understood to those that are suspected to be important but are not well understood. In general, the importance of this area can be justified on scientific grounds and on the likelihood of demonstrating connections to practical problems such as agricultural productivity through changes in the hydrologic cycle, air temperature, or global climate.

2.1.1 Decrease of Solar Irradiance

Solar irradiance (the amount of solar energy reaching the ground) is itself one of the important components of climate. It is a primary factor in determining the surface temperature of the earth, the source of energy for photosynthesis, and the energy supply for evaporation of water from the earth's surface; these functions make irradiance a major factor driving the hydrologic

cycle. It is also one of the main factors controlling the energy supply for atmospheric motions (wind). Fortunately, it is also directly observable as are many of the atmospheric aerosol properties that influence it. In particular, research over the past decade in the United States has successfully determined the role of atmospheric aerosol in governing solar irradiance. Both direct measurement of solar irradiance and measurement of aerosol properties demonstrate that the particles in the air above a large part of the eastern United States cause an average decrease in irradiance of approximately 7%. Episodes, especially during the summer, cause irradiance losses of 15% to 20%. the internal consistency of these two sets of data with observations of degraded visual range and atmospheric turbidity, along with studies of aerosol composition, demonstrates conclusively that sulfate and elemental carbon (soot) are the main causes of the observed effects. These aerosol constituents are produced in the same region by a variety of urban and industrial sources.

2.1.2 Atmospheric Stability

The presence of light-absorbing aerosol redistributes energy so that less goes into the ground and more goes into the air. This can cause an increase in the static stability of the boundary layer or, equivalently, a reduction of vertical turbulence that mixes pollutants throughout the boundary layer. Thus, near-ground-level emissions (e.g. automobile exhaust) will stay concentrated longer, and high-level emissions, such as sulfur dioxide (SO_2) emissions from power plant stacks, will travel farther and longer before being mixed to the ground where SO_2 can be removed by dry deposition. The latter could result in

an increase in the amount of SO_2 from power plant stacks that is converted to sulfuric acid.

The reduction in vertical mixing (convective activity) could modify the frequency of formation and lifetime of cumulus clouds, with resulting effects on albedo and distribution of rainfall. The heating rate of the atmosphere due to typical levels of atmospheric aerosol is sometimes comparable to the rate caused by nonradiative cloud processes. Thus, there is potential for modification of cloud formation, growth, and decay. As an example, satellite images show reduction of cumulus activity in aerosol-laden plumes.

There are immediate, short-term research projects that could define the significance of aerosol on atmospheric stability:

(1) Continue work with radiative models in order to define the effect on the vertical temperature structure of aerosol absorption and to examine the relationship between aerosol absorption and atmospheric stability.

(2) Examine the satellite and meteorological records for suitable incidents and analyze these to determine if the are caused by stability enhancement due to aerosols. (See Atwater, 1972, 1975, 1977; Bergstrom and Viskanta, 1973; Viskanta and Daniel, 1980.

2.2 MODIFICATION OF THE OPTICAL PROPERTIES OF CLOUDS

An increased concentration of submicron particles in the troposphere may have two separate impacts on cloud albedo:

(1) If the particles contain graphitic carbon, and are incorporated into clouds either in cloud drops or as interstitial aerosol particles, the effect of the particles will be to make clouds "grayer" than they would be if they were

composed of pure water drops. The absorption can be very small; for example, a typical single-scattering albedo (W_o) for a polluted cloud might be equal to 0.995. However, the effects of multiple scattering (and to a lesser extent the lends effect of the water around a black core) can cause a substantial lowering of cloud albedo. Graphitic carbon is found in rain in mid-latitude, continental regions at concentrations which could lead to significant reductions in cloud albedo.

(2) If the primary effect of the submicron particles is to increase the number of activated droplets per unit volume, the albedo, which depends on the total surface area of the drops, will <u>increase</u>.

Effect (1) above is most important in thick clouds; effect (2) is important in thinner clouds. The calculations of (albech changes) (Twomey, 1976; Ackerman and Baker, 1976; Welch et al., 1980) have not always included the effects of the finite horizontal extent of clouds, which is important. However, considering only layer clouds, which is important. However, considering only layer clouds of essentially infinite extent, the effects are potentially large enough to make this a vital area for study.

2.2.1 Modification of Cloud and Precipitation Patterns

The cloud systems responsible for most of the precipitation (greater than 50% annually and 75% in the summer) in the northeast and middle United States are mesocale convective systems, which consist of clusters of convective clouds, both shallow and deep, often meeting aloft in stratiform anvil clouds. Roughly half of the precipitation falls from the anvil clouds and half falls from convective cloud cells. The systems, roughly 10,000 km^2 in extent, are initiated

when some large-scale forcing, coupled with a conditionally-unstable environmental sounding, causes convection that is strong enough to form the cumulus cells. These systems are short-lived and dissipate, heating and moistening the environment to varying degrees at all levels of the atmosphere. Precipitation ceases when the environmental conditions no longer support the moist convection. Average heating rates due to cumulus activity typical of these mesocale systems in mid-latitudes are on the order of 5°C to 10°C per day in the column where condensation occurs. These rates are observed and calculated from models that reproduce precipitation onset, duration, and rate quite well.

In polluted regions, atmospheric heating rates due to solar absorption by particles are about 10% to 50% of these values. Thus, it appears that the radiative heating may also be important in modifying environmental temperature soundings and hence could modify formation and precipitation patterns. This effect of direct heating must be considered together with the optical effects described previously. Moreover, if heating is partially due to increased concentrations of absorbing particles, the particle loading effect on the microphysics must also be included in any study.

2.2.2 Production and Vertical Transport of Particles by Clouds

Inside droplets, oxidation of SO_2 to sulfate ($SO_4^=$) increases the amount of particulate matter in the atmosphere. Moreover, clouds redistribute existing particles. The transport of materials inside clouds can bring pure, unmixed cloud air from the cloud base to the top of thunderclouds. On the other hand, material entrained at the cloud top can mix with cloud air to form negatively-buoyant parcels that can descend almost to the cloud base. Dissipation of clouds during this transport process, initiated by entrainment of dry air, leaves new

during this transport process, initiated by entrainment of dry air, leaves new particles (left after evaporation of cloud droplets) dispersed in a column from the cloud base to the cloud top. All these processes have very important impacts on redistribution of "contaminants," not only in the troposphere, but up to the tropopause and beyond in some cases. These materials include not only the original particles that entered at the cloud base, but also any products of liquid-phase chemistry due to incorporation of gases during entrainment. Repetition of the birth-death cycle of cumulus clouds can substantially modify mean atmospheric profiles of particles. Note that in the course of the transport of cloud-base and cloud-top materials up and down, there may be a modification of ice-phase processes, which are of interest in precipitation formation.

2.2.3 Haze Stabilization

Liquid water can be stabilized in a contaminated (polluted) atmosphere in two ways. First, water condenses on hygroscopic or deliquescent nuclei at humidities below 100% and forms energetically-stable small drops. Second, some organic materials can form thin films on small water drops; one monolayer is sufficient to slow the evaporation of water. At realistic concentrations of the substances capable of forming these films, only very small drops will be affected, because there is not enough organic material to create monlayer coverage on large drops on realistic time scales. Both of these mechanisms will stabilize haze.

2.3 A PRELIMINARY ASSESSMENT OF THE EFFECTS OF HAZE ON AGRICULTURE

Haze levels over major agricultural areas such as the Corn Belt of the United States reduce ambient temperature levels in the plant canopy and soil

surface. These reductions may delay planting dates and alter growth rates. Such alterations in the growth period and growth rates of the crop may reduce crop yields.

2.3.1 Importance of Effects

A delay in planting dates is equivalent to a shift in latitude. For example, a delay of 7 to 10 days in planting beyond historically "normal" planting dates in central Illinois is comparable to moving 160km north, shortening the growing season. Such a shift to a more northern growth zone would represent a 4% to 6% loss in soybean yield unless suitable substitute soybean cultivars are available.

2.3.2 Research Objective and Strategy

A pilot program to determine the relationship of haze and other environmental conditions to soil temperatures and plant microclimatic conditions should be supported. Resultant changes in ambient temperatures can then be linked to effects on crop planting dates and growth rates. Once relationships between haze, planting date, and growth rate are established, economic models that incorporate the relationship between planting date and crop yield can be applied to determine expected crop loss and economic damage associated with alternative haze levels. Such an economic model of soybean, wheat, and hay production is currently being used in EPA's NCLAN program (Adams and McCarl, 1984)

A multidisciplinary approach must be taken for this work, with a cooperative effort between three specialties. First, atmospheric scientists must develop the relationship between the spatial and temporal distribution of regional haze and the microclimatic conditions experienced by the crop. Second, agronomists must identify recent planting dates, cultivation patterns, and growing seasons in the Corn Belt; haze-induced alterations in these parameters will become input into economic assessments. Third, economists must apply the model of Corn Belt agriculture that reflects yield changes arising from the haze-induced microclimatic alterations. Finally, the atmospheric scientists must connect the amount of haze and its properties to sources, in order to understand and plan control strategies.

RESEARCH NEEDS

The research needed to investigate the significance of aerosol-induced climate changes was discussed during the workshop. These needs are organized by the scale of the phenomena, from single aerosol particles to regional climate involving large geographic areas. Information developed in each research category will be used in the research performed for the next larger scale. The basic requirement in the research is to view the climate alteration question as part of a larger problem of atmospheric chemistry, visibility degradation, acid rain, and air pollution control.

3.1 FORMATION AND TRANSFORMATION

Because of the efficient interaction of light with submicron particles and because these particles are predominantly formed as secondary reaction products in the atmosphere, it is crucial to understand the dominant pathways by which gases are transformed into particles. Primary candidate gases of concern are sulfur dioxide, nonmethane hydrocarbons, and oxides of nitrogen. It is thought today that the initial chemical attack on these gases occurs via the hydroxyl radical (OH•), which is by itself a product of photochemistry in the atmosphere. In addition, olefin compounds are attacked by ozone (O_3). The concentration of the key chemical gas-phase oxidant, OH•, is determined by a variety of meteorological and chemical factors, including solar light flux in specific wavelength bands; the amount of water vapor; and the concentration of oxides of nitrogen, carbon monoxide, hydrocarbons, and ozone.

When clouds are present, water-soluble pollutants (such as sulfur dioxide) and photochemically-generated oxidants (such as ozone and hydrogen peroxide) enter the liquid-water phase of the cloud droplets, where reactions can take place that do not occur in the gas phase. Because air is processed through clouds many times before pollutants are removed, a substantial amount of reaction can occur. The cloud evaporation process releases the reaction products as aerosol particles that have grown in mass due to chemical reaction in the cloud droplets. It is therefore prudent to link the aerosol formation processes to the "photochemical reactivity" of the atmosphere, and to define certain parameters in an attempt to characterize their chemical air-mass-related reactivity, such as (1) the ratio of oxides of nitrogen to nonmethane hydrocarbons and (2) the solar flux for the ozone dissociation.) It becomes obvious that radiative climate is indeed governed by very complex chemical, physical, and air-mass-related parameters; thus, its control may indeed require detailed knowledge of many atmospheric chemistry processes, many of which involve more than one pollutant and may be nonlinear.

Light absorption by aerosols is largely determined by the graphitic carbon content of the particles. Incomplete combustion of hydrocarbons is the source of graphitic carbon entering the atmosphere. Man-made sources include internal combustion engines; production of steam, electric power, and heat; and prescribed burning in forests and agricultural lands. To understand how various sources of pollutants alter regional climate, the relative proportion of carbon and other

substances in the aerosol and an inventory of emission source strengths must be determined.

Finally, measurement techniques to measure chemical speciation of particles, either collected on filters or in cloud/rain water, still need development and validation.

Specific needs in the areas of particle formation and transformation include the following:

- Study the gas-to-particle reactions for two types of compounds:
  -- Sulfur compounds, particularly SO_2. Confirm that the formation of sulfate aerosol initiated by OH• is not a chain terminating reaction with respect to OH•.
  -- Organic compounds. These reactions, initiated by OH• or O_3, lead to the production of low-volatility organic compounds that can either nucleate or condense on existing particles. Also of interest are the reactions involving oxides of nitrogen and organic compounds leading to organic nitrate aerosols.
- Improve measurement capabilities for inorganic and organic nitrate aerosol.
- Develop source inventories for elemental carbon and residual organic material. Include information on size distribution for these primary emissions.

- Determine the impact of evaporating clouds on the chemical composition and size distribution of the residual aerosol. Assess the importance of this aqueous-phase mechanism for aerosol formation e.g., sulfate aerosol formation).

- Improve measurement capabilities for particulate carbonaceous material and elemental carbon.

3.2 OPTICAL PROPERTIES

The optical properties of aerosols revellent to climate alteration need to be characterized. These properties include the phase function (light scattered from aerosol as a function of angle) and the scattering and absorption coefficients. To understand the relationship between optical properties and the aerosol, it will be necessary to characterize the particle-size distribution, concentration, and chemistry of the aerosol and to measure relevant meteorological parameters.

The research needs for determining the aerosol and cloud optical properties include the following:

- Obtain high-quality total solar irradiance data at key locations over a long period (several decades) on a continuous basis. it was suggested that the Department of Energy Solar Meteorology Training Center facilities be reactivated and that possible two or three sites be relocated.
- Measure properties relevant to the question of climate modification under conditions of known aerosol sources in various parts of the United States and during various seasons. These properties include phase function, scattering coefficient, and absorption coefficient.
- Study relevant infrared processes, especially those that might compensate for heating or cooling caused by the effects of aerosol particles on solar radiation.

3.3 CLOUD MICROPHYSICS

Extensive experimentation and analysis of cloud behavior, in particular induced weather modification, has been conducted over the last 20 years. However, many of these large-scale experiments have lacked the determination of particle chemistry and optical properties required for linking the results either to particle sources or to climate effects. Two approaches should be considered: cooperative studies with future field studies of clouds by other agencies, and the development of diagnostic studies to test the postulated questions and develop measurement techniques. The cloud microphysics research needs include the following:

- Critically review existing knowledge of the effects of man-made particles on cloud formation and dissipation processes, including glaciation. Formulate programs to fill in gaps in knowledge.
- Determine the state of elemental and organic carbon particles in clouds. Do they remain mainly as free particles, or are they incorporated in cloud droplets? This question is important in considering optical properties, heat balance, and cloud albedo.
- Examine the effects of various types of particles, including organic, on the persistence of fog and haze.

3.4 AEROSOL INFLUENCE ON RADIATION AND HEAT BUDGETS

An essential step in aerosol research demonstrating aerosols cool the ground and heat the air in the planetary boundry layer (PBL). This step is critical, because if these first-order effects cannot be detected under extreme conditions of heavy haze, then the program needs to be reassessed.

It is expected that the investigation will require both one-dimensional mathematical models of the vertical temperature structure and carefully conducted experiments of radiative fluxes and meteorological parameters, in addition to information the particle and optical characteristics detailed previously.

These research needs include the following:

- Determine the magnitude of the insolation reduction caused by haze in various regions and seasons.
- Investigate the effects of radiative heating of the haze layer on the surface energy budget. Estimate the change in the mean relative humidity of PBL due to decreases in evaporation. Determine to what extent the vertical mixing (ventilation) in the PBL is suppressed by the stabilizing effect of redistributing solar energy from the ground to the haze layer.
- Study the effect on albedo of changes in the bulk properties of clouds (e.g., the number concentration) caused by particles.

3.5 DISTRIBUTION OF AEROSOLS AND CLIMATOLOGY

It has been demonstrated by Husar et al. (1976) that air pollution episodes affecting concentrations of aerosol pollutants and reducing visibility involve haze blobs. These haze blobs will likely produce the largest aerosol-induced effect on climate. Establishing long-term trends of observable meteorological parameters linking aerosols to climate is the eventual goal.

Research needs include the following:

- Investigate the regional and seasonal distribution of haze by using all of the existing synoptic and satellite data sets. Establish long-term trends.

- Establish cause-and-effect relationships between haze and regional climate trends.
- Specify the instrumental requirements, such as appropriate wavelengths and band widths, for remote sensing of haze properties from satellites and develop a cooperative program with the National Aeronautics and Space Administration.

3.6 AEROSOL IMPACT ON VEGETATION

The most likely effect associated with aerosol alteration of solar flux and atmospheric thermal structure is on plant seed germination and growth. This work will require the micrometeorology and climatology information developed by this program. Only after the biological significance is established would the economics analysis be needed. The research needs include the following:

- Investigate the magnitude of the direct and indirect influence of aerosols on vegetation. Direct effects include an increase in the diffuse-to-direct solar radiation ratio and lowered ground temperature. Indirect effects include regional climatic changes in quantities such as ground and air temperature, relative humidity, cloud amount, and precipitation.
- Utilize the work already being done in this area by ongoing climate investigations, such as the carbon dioxide study.

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APPENDIX

ABSTRACTS OF WORKSHOP PAPERS

ASSESSING THE ECONOMIC CONSEQUENCES OF ENVIRONMENTAL CHANGE ON AGRICULTURE

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Introduction

Agriculture and other managed ecosystems both contribute to and are affected by environmental degradation. Examples are non-point sources of water pollution and air pollution. In the first case, intensive production practices common to U.S. agriculture exacerbate soil erosion and require high levels of chemical inputs. As a result, agricultural production leads to reduced water quality for downstream water users. Conversely, the effects of ambient air pollutants from anthropogenic (primarily urban) sources on plant growth and crop productivity are well documented. Each agricultural externality is important to policy makers in promulgation of environmental standards under the Clean Air and Water Acts.

Present Research

My research during the last five years has focused on the economic consequences associated with both types of environmental effects. The more recent emphasis has been on assessing the economic consequences of alternative ambient ozone levels on agriculture, including effects on producer and consumer well-being. Initial interest in this area in 1978 was motivated by the need to improve on the incorrect or inappropriate procedures used in past assessments of the benefits of pollution control to agriculture. Attempts to apply these types of economic methodologies for policy use indicated that the techniques were traceable but that the biological data on crop response were not generally appropriate for use in such economic assessments. The need for crop response data to support secondary National Ambient Air Quality Standards and to provide input into economic assessments motivated the Environmental Protection Agency to establish the National Crop Loss Assessment Network (NCLAN). In order to improve economic assessments, NCLAN funded a series of regional and preliminary national economic assessments in 1982 and 1983 intended to test methodologies, define data needs and provide benefits estimates for alternative ozone standards. Some of the important conceptual dimensions and relevant biological data requirements of economic assessments of vegetation effects are illustrated in Figure 1.

The economic research arising from NCLAN has addressed a number of research policy questions in addition to providing benefits estimates of alternative ozone levels. Specifically, the relationship between the type and quantity of biological data and resultant economic estimates has been extensively explored. At the same time, numerous economic methodologies have been empirically tested. The empirical results from a series of NCLAN economic regional studies are reported in Table 1. The benefits of ozone control represented in Table 1

represent benefits to producers and consumers and are derived from economic assessment methodologies intended to capture the important economic dimensions portrayed in Figure 1. Such methodologies are capable of addressing vegetative yield changes due to any type of environmental or technical change. The results of this research have also established that biological data are important in the formation of economic hypotheses and as input into economic models but exhaustive and prolonged experimentation is not always necessary to perform credible economic assessments. The value of that biological information, in terms of improved policy decisions (measured in economic efficiency terms), appears to diminish rapidly. Further, some economic methodologies minimize the need for costly experimental data by making effective use of the information inherent in producer behavior. The collective implication of the research projects is that there are research gains from combining biological and economic needs at the conceptual stage -- gains in terms of reduced research costs of each discipline in meeting policy objectives keyed to economic values.

Future Research

The research thrust in the NCLAN and peripheral research projects has been on agricultural crops. To the extent that economic processes and crop responses (to major pollutants) are fairly well documented, economic assessment of the effects of environmental change on agriculture is one of the more tractable research topics. While the economic consequences of environmental change on agriculture appear substantial, the magnitude of these effects vis a vis other welfare categories (e.g. materials, other vegetation values) is not well established. Capturing the economic effects of environmental change on nonmanaged ecosystems conceptually and empirically more difficult and hence few economic assessments of these phenomena exist. In addition to applying benefit analyses to a broader set of vegetative effects, the issue of ecosystem service flows (diversity values, recreation and visibility values) as they are effected by environmental change is not well understood. This potentially important policy area is of interest to some environmental economists but little applied research has been completed. The policy utility of the few studies in the literature is limited to specific costs and hence is insufficient to gauge either directions or magnitude of probable economic effects at the national level. Assessing and integrating these diverse economic effects into a total benefit-cost analysis poses major challenges and perhaps some of the greatest policy payoffs for environmental economics. Future research in the area of benefits analyses should include the following topics:

1. More environmental interactions need to be considered in assessments of environmental effects on agriculture. Present assessments are piece-meal in that they isolate only one environmental effect, e.g., ozone in the absence of SO_2 moisture stress, UV-B radiation and other interactions.

2. Integrate the benefits across all receptors such as forest and other unmanaged ecosystems which previously have not been considered.

3. Visibility values may be one of the most immediate economic developed procedures to test extrapability of current site specific visibility values to broader regional scales for use in policy analysis.

4. Examine preservation values. Determine the extent to which the public is willing to pay for the preservation of the environment for future generations.

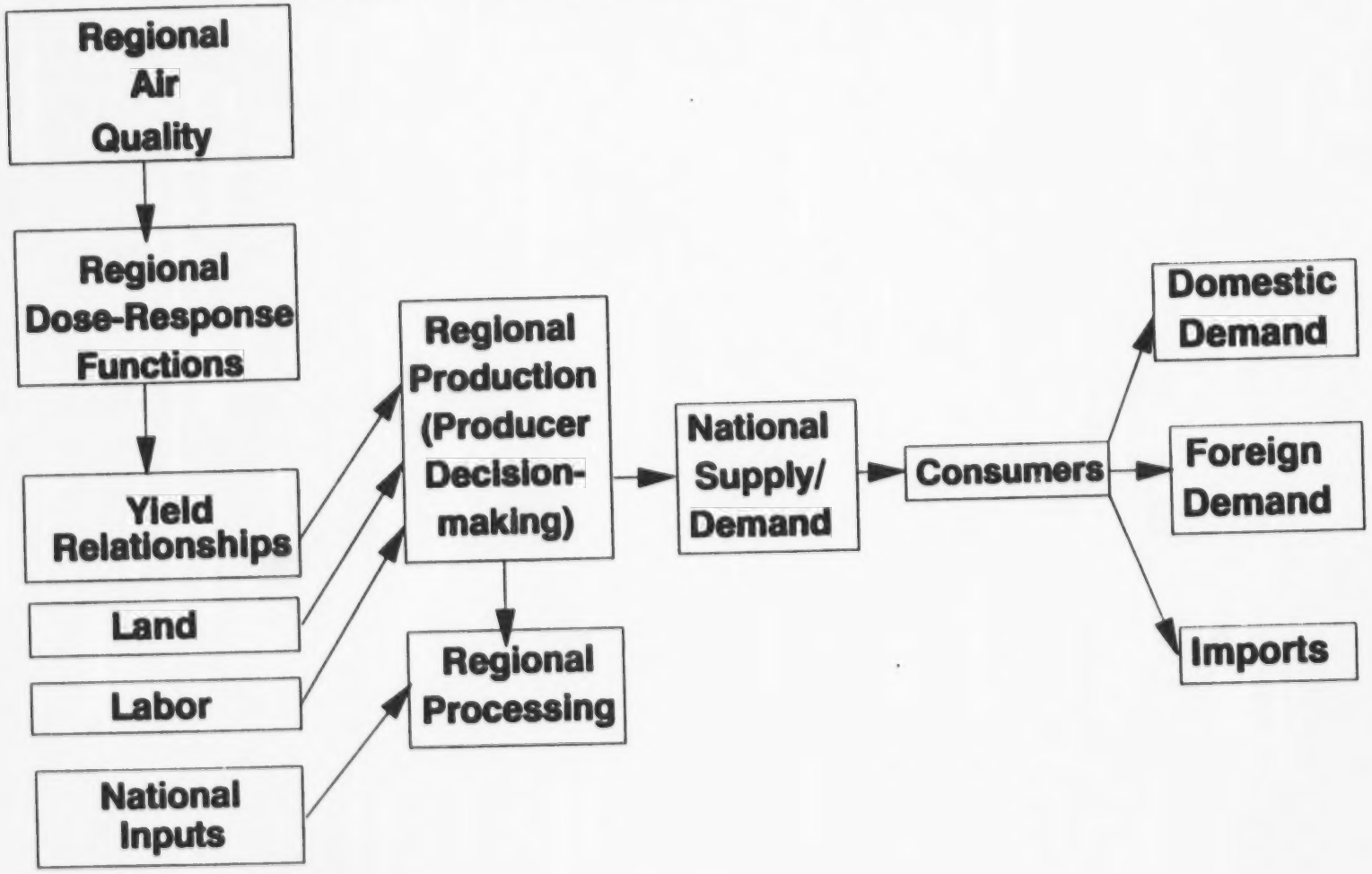
5. Examine a broader range of environmental mitigative procedures, such as investigating alternative sitings of point sources as an alternative to present in-situ control strategies.

TABLE 1. SUMMARY OF NCLAN REGIONAL ASSESSMENTS

INVESTIGATORS	REGION	OZONE CONTROL ASSUMPTION[a/]	BENEFITS OF CONTROL (MILLIONS)	MODEL AND ASSUMPTIONS
ADAMS	CORN BELT	.04 ppm	$700 - 1,100	ECONOMETRIC. ANALYSIS OF CORN, SOYBEANS AND WHEAT
ADAMS & McCARL	CORN BELT	.04 ppm	$668	MATHEMATICAL PROGRAMMING. ANALYSIS INCLUDES CORN, SOYBEANS, WHEAT AND LIVESTOCK-EXPORT SECTORS
DIXON ET AL.	ILLINOIS	25% REDUCTION FROM AMBIENT	$50 - 180	DUALITY. ANALYSIS BASED ON CASH GRAIN FARMS IN ILLINOIS. EFFECTS ARE ON PRODUCERS.
HOWITT ET AL.	CALIFORNIA	.04 ppm	$40	MATHEMATICAL PROGRAMMING. ANALYSIS LIMITED TO EIGHT ANNUAL CROPS

a/ Ozone control assumes all rural ambient concentrations are reduced to .04 ppm seasonal seven-hour average. Level of control ranges from 10-25 percent as measured against 1980 ambient concentrations.

Figure 1. Flow Chart: National Economic Assessment of Environment Change on Agriculture



ATMOSPHERIC AEROSOLS AND CLOUDS

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The impacts of particulate pollutants on visibility and regional climate are largely determined by aerosol-cloud interactions. Our research has centered on the following two questions concerning the link between clear air aerosol concentrations and cloud processes.

(a) Given the statistical distributions of wind and precipitation fields, is it possible to predict the statistics of airborne concentrations and wet removal fluxes of aerosols?

(b) What is the relationship between the mixing of cloudy and environmental air and the development of embryonic raindrops?

In the next few paragraphs I will briefly describe our research to date in these areas, and then our current research, in which the two are united.

(a) Stochastic models of wet removal

We (Baker et al., 1979, 1984) have developed a stochastic conservation equation for the concentration of particles, $c(x,t)$

where $\underline{u}$ is the wind velocity, Q the generalized source function and S the sink. We solved Eq. (1) assuming that only the wet removal term in S is stochastic, and derived the moments and time-lagged autocorrelation of c and of wet-removal fluxes in terms of those of S. We are now adapting these ideas to a numerical model of transport of air pollutants in which not only mean values but also the moments of the concentrations and the wet deposition fluxes are calculated at each time step. Input data for the model are the gridded wind, source and

precipitation fields from the Northeastern U.S. and parameterized results of cloud models to be discussed below.

(b) Entrainment and the development of Precipitation

Broad droplet spectra are required for both warm and cold rain initiation [1] Models of condensation which assume homogeneous mixing produce narrowing of the spectra with time (curve H. Figure 1). In a series of theoretical and experimental papers (Baker and Latham, 1979; Baker et al., 1980, a,b; 1982,a,b) we suggested that the answer to this puzzle, which has obvious implications for cloud chemistry and deposition via precipitation, my lie in the inhomogeneous nature of entrainment, or mixing between the cloud and its environment.[2] If mixing takes place nonuniformly, different parcels have different supersaturation histories (and presumably different chemical pathways as well). Moreover, we (Jensen et al., 1984) have recently confirmed earlier ideas by Squires (1958) and others that entrainment often occurs at cloudtop, and not through the sides of clouds as assumed in classical models. These newly understood features of the entrainment process greatly modify ideas of scavenging of pollutants by clouds.

We are now attempting to unite the transport models with our models of entrainment and precipitation development. We consider boundary layer

[3]

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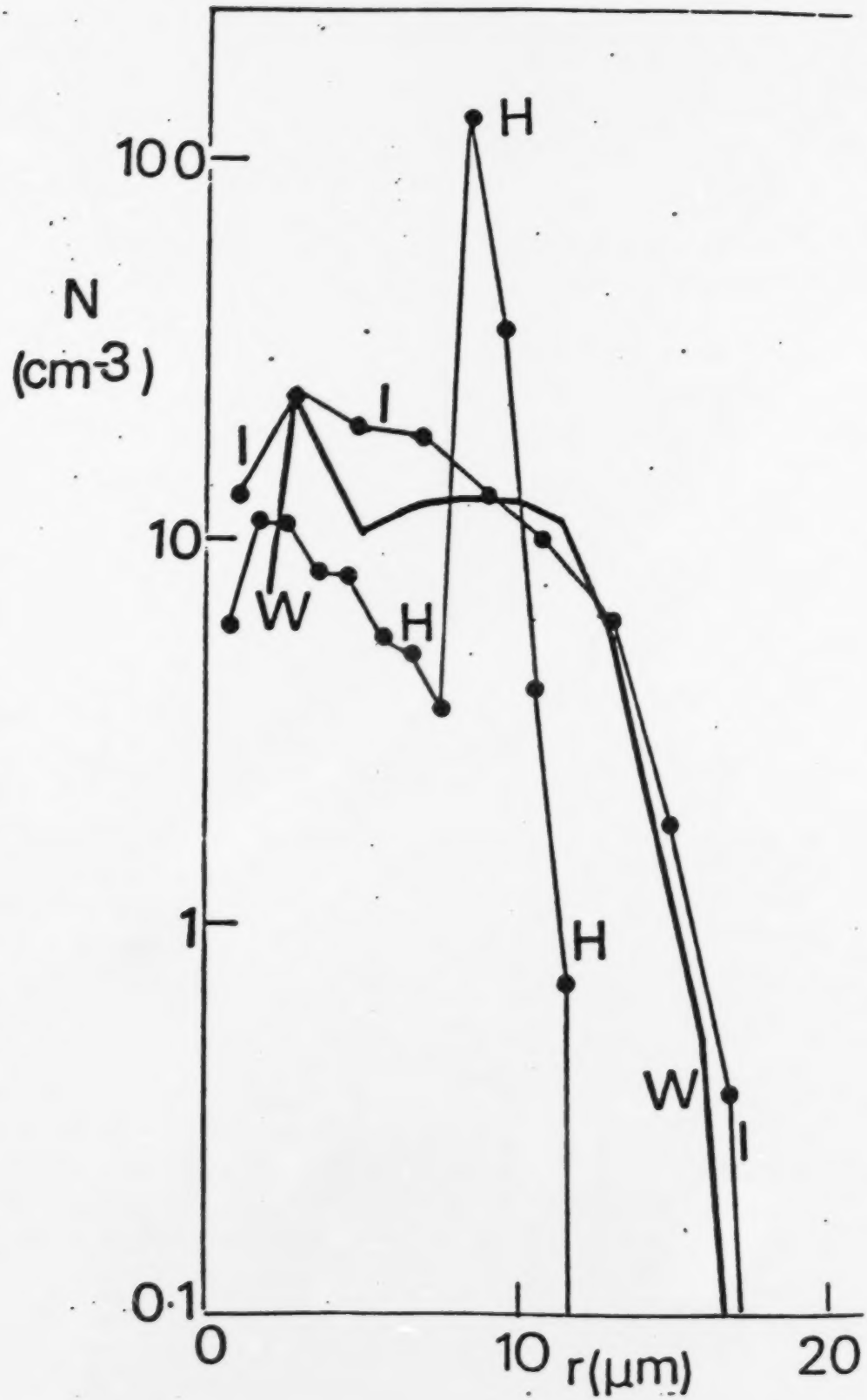
[1] BAKER.1
Observations by Warner (1969), curve W in Figure 1, are an example. However, classical

[2] BAKER.2
A numerical model which considers non-uniform entrainment was used to predict curve I in Figure 1. which agrees quite well with the observations.

[3] Figure 1. Size distributions in cumulus. W, measured by Warner (1969); H, calculated by classical model assuming homogenerous mixing; I, calculated by inhomogeneous model; (from Baker and Latham, 1979).

FIGURE 1.



convergence near a convective system and subsequent deposition by it as parts of the same process. We use a cumulus parameterization on the mesoscale by Kuo (1974) adapted to the case of the convective clusters which are responsible for most of the precipitation in the middle and Northeastern U.S. In this scheme boundary layer convergence of moisture and heat determine the onset, area coverage and rate of convective precipitation which is assumed to occur in short-lived cumulus cells. We will study the development and characteristics (including variability) of wet deposition fluxes as functions of mesoscale forcing, i.e., thermodynamic soundings, wind fields, convergence of mass, moisture and heat, and diabatic heating rates. We plan to apply the model both to sulfates and to carbon-containing particles. Initial calculations show that in polluted conditions the magnitude of the diabatic heating due to absorption of solar radiation by these particles is comparable with the heating due to cumulus activity. This may represent an important feature of the air pollutant-regional climate interaction which can only be studied in a large-scale, dynamic contest.

II. Directions of Future Research

The link between atmospheric pollutants and regional climate is determined by the lifetimes of the pollutants and hence their removal. On the other hand, the very presence of a pollutant may influence its removal. These interactions should be studied both experimentally and theoretically on their natural scales, which range from the cumulus to the mesoscale. Most crucial to further development are experiments designed and carried out by cloud physicists and chemists together) which simultaneously measure the fluxes of tracers into selected cloud systems along with cloud physical and chemical parameters and the wet deposition fluxes.

AEROSOLS AND ELEVATED MIXED LAYERS

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Background

My early work on Saharan dust concerned the meteorological aspects of the large-scale dust transport problem; efforts to understand more about dust led me to become interested in the chemical, physical and radiative nature of the aerosol. During the 1974 GATE program, I conducted an experiment on the island of Sal in the Cape Verde chain west of the African coast. The object of this experiment was to measure with a variety of short wave radiometers the optical thickness of the dust and thereby to chart the daily fluctuations in the total columnar dust loading. This field program provided the stimulus for further investigations of the Saharan dust phenomena from the standpoint of its radiative properties, including the large-scale distribution of optical depth during dust outbreaks and the radiative heating rates of Saharan dust.

After I came to Penn state in 1974, I continued to work on aerosols but the emphasis began to shift toward the modeling of large-scale dust transport. One of my most significant conceptual realizations concerning dust is that most aerosol, including anthropogenic material, is introduced into troposphere through the atmospheric boundary layer. Under free convection, the boundary layer becomes well-mixed, its potential temperature, water vapor mixing ratio and aerosol content tending to assume a slowly changing distribution with height. The remarkable feature of Saharan dust is that it is so widely distributed over the ocean. Moreover, there are many other important sources of continental dust,

such as the other semi-arid source regions of the world, India, Iran, China etc. Examination of atmospheric soundings downwind of such source regions, whether over ocean or land, tend to show that the dust layer can be identified as a well-mixed strata, typically with a base at 1-2 km and a top close to the level of the top of the source mixing layer, which may reach altitudes of 4-6 km. This elevated mixed layer is typical of boundary layer air which as been advected from its source, whether that source be Africa, the Middle East, Mexico or Texas.

Present Research Status

Modeling both the radiative and meteorological aspects of the dust depends on a knowledge of the vertical distribution and thereby on being able to adequately represent the structure of elevated mixed layers in atmospheric models. Therefore, it is imperative that atmospheric models contain detailed boundary layer physics and adequate vertical and horizontal resolution. In addition, one must possess a knowledge of the surface characteristics (soil moisture, etc) in order to model the formation of elevated mixed layers, whether they be of semi-arid or not.

A further difficulty involves the specification of the aerosol sources and a proper formulation of how dust is lifted and deposited. At Penn State we have been trying to model the formation and movement of elevated mixed layer air and we have recently begun to include a Saharan-type aerosol as a passive atmospheric variable in the model. We are addressing the various problems of aerosol physics, aerosol sources, and the difficulties of treating elevated mixed layers within a large-area model. We hope soon to consider the aerosol as a radiatively active constituent in the models.

The Future

Our experience with radiation calculations and with one- two- and three-dimensional atmospheric models strongly suggests that it is very dangerous to

anticipate how a system will truly behave by simply modeling the change in one parameter or physical effect. For example, radiation calculations based only on the solar spectrum or a part of the solar spectrum may suggest a warming or cooling based on a chosen absorption coefficient and surface albedo. Neglecting the remainder of the electromagnetic spectrum may lead to erroneous conclusions. In an analysis of aircraft data made over St. Louis during the Regional Air Pollution Study (RAPS), we were able to show that there was indeed a significant short wave warming of the boundary layer but that the long wave cooling almost exactly balanced that warming. Further, it is apparent that full-spectrum one-dimensional radiation calculations alone may still yield the wrong answer without consideration of the total surface energy budget. Both measurement and calculation show very large radiation warming by dust over deserts. On the other hand, an analysis of the total surface energy budget would also show that much of the solar energy absorbed by dust would have been otherwise used to warm the boundary layer anyway, because almost all of the solar radiation reaching the ground would be returned to the atmosphere via the flux of sensible heat from the surface. Of course, the vertical distribution of dust affects the vertical distribution of the radiative heating.

It need not be emphasized that the conclusions based even on simple models are subject to great uncertainty because of uncertainty regarding concentration and the radiative properties of the dust over the whole solar spectrum. We suggest, therefore, that to answer the question of the effects of aerosols on climate a minimum requirement is to consider both the full-spectrum radiation problem and the surface energy budget in tandem. To further assess the effects of the radiation warming or cooling on climate requires an extension to three-dimensions and possible to long-range large-area (or global) models. Our

experience here suggests that sensitivity studies using complex models can yield ambiguous results in any single simulation.

Because of uncertainties involved in the knowledge of the aerosol parameters, not to mention the atmospheric interaction, we recommend that before any firm conclusions are advance, an effort be devoted to studying the sensitivity of atmosphere-aerosol models to uncertainties in the basic parameters in order to answer the following questions: (1) is one entitled to assess the impact of aerosols on climate given the present level of ignorance and (2) what needs to be known in order to calculate the meteorological impact to within a given tolerance of error? We suggest also that a goal of numerical modeling of aerosol transport be concerned with specifying surface sources, allowing the distribution in the atmosphere to evolve from initial conditions in the model. We are far from realizing that objective.

THE INFLUENCE OF SULFATE AND ELEMENTAL CARBON AEROSOLS ON REGIONAL SCALE RADIATIVE CLIMATE

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My research interests are largely dictated by my being a chemist with graduate study in meteorology, followed by post-doctoral study in cloud physics. The earliest work was related to the influence of humidity on aerosol particles at relative humidities (RH) less than 100%, a topic which demonstrated the importance of the molecular (or ionic) form of the aerosol particles. The University of Washington's integrating nephelometer (Charlson and Ahlquist, U.S. Patent 3,563,661, 1971) was originally devised as a closed chamber device to allow control of RH and study of aerosol optical response. The closed chamber allowed absolute calibration with gases (e.g., CO_2, CCl_2F_2) and thus a means for continuously measuring the scattering component of atmospheric extinction. After developing applications of this instrument to the problem of atmospheric visibility, a major effort was undertaken to characterize the hygroscopic nature of submicrometer light scattering tropospheric aerosols. Collaboration with the late K. T. Whitby and colleagues demonstrated that there was almost always a high correlation ($r^2>0.9$) between the mass concentration of accumulation mode particles and the scattering component of extinction due to particles, sp. Further, the efficiency of scattering is in agreement with Mie computations for the measured size distributions. The results of the combined efforts also demonstrated that this submicrometer mass mode is always hygroscopic in eastern parts of North America and it is dominated by sulfate compounds with composition ranging between H_2SO_4 and $(NH_4)_2SO_4$ (Charlson et al., Science, 184, 1974).

Further studies of the humidity dependence of light scattering demonstrated that these sulfate aerosols were not limited to urban settings but were distributed over a region of at least 1000 km extent (Weiss et al., Science, 195, 1977). Sulfate aerosol mass concentration was determined along with the molecular characterization by response to humidity showing that $_{sp}$ is not only well correlated with submicrometer mass, but with sulfate concentration as well (Waggoner et al., Nature, 268, 1976).

The questions that then arose were:

- What were the sources of this prevalent sulfate haze?
- Is the haze natural or man made?
- It obviously controls atmospheric visibility but is it important for climate?

While the RH work was in progress, another effort yielded a means to measure the light absorption coefficient due to particles (Lin et al., Applied Optics, 12, 1973). Simultaneous measurements of σ_{sp} and σ_{sp} showed that the eastern U.S. was also influenced by persistent absorption due to elemental carbon C(O). These two measurements are combined in Table 1 and yield a direct determination of the albedo of single scatter $\tilde{w}$, which has values around 0.9 in the eastern U.S. down to as low as 0.5 in some cities (Charlson and Robinson, unpublished; see also Waggoner et al., Atmos. Environ., 15, 1981. The lack of a significant difference in the values of extinction measured in urban and rural locations points to the regional, as opposed to local, nature of haze.

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Table 1

Site A. Urban	Scattering Extinction ± standard deviation $\sigma_{sp_g} \pm s_g (m^{-1})$	Back-Scatter Ratio R(90°)	Albedo for Single Scatter $\tilde{w}_g$	Number of Determinations N
1. Phoenix, AZ 11-17-78/11-23-78	3.0E-4 1.9E-4 1.2E-4	--	0.68 0.63 0.59	20
2. Denver, CO (Henderson) 11-10-73/11-15/73	9.7E-5 3.4E-5 1.2E-5	0.15 0.12 0.11	0.69 0.50 0.37	13*
3. Denver, CO (Trout Farm) 11-15-73/11-21-73	1.4E-4 5.8E-5 2.3E-5	0.13 0.11 0.09	0.67 0.54 0.43	23
4. Denver, CO 11-20-78/12-20-78	1.8E-4 6.2E-5 2.2E-5	--	0.73 0.61 0.49	103
5. Seaatle, WA (Industrial) 3-18-77/4-10-77	9.7E-5 3.6E-5 1.4E-5	--	0.76 0.65 0.55	43
6. Seattle, WA (Residential) 5-24-77/6-11-77	5.8E-5 3.5E-5 2.1E-5	--	0.87 0.78 0.70	69
7. Portland, OR 1-16-77/3-2-77	2.1E-4 7.4E-5 2.7E-5	--	0.67 0.55 0.45	159
8. St. Louis, MO (St. Louis Univ.) 9-28-73/10-4-73	1.1E-4 6.5E-5 3.7E-5	0.11 0.10 0.07	0.70 0.59 0.49	50

Table 1 Continued

Site A. Urban	Scattering Extinction ± standard deviation $\sigma_{spg} \pm s_g (m^{-1})$	Back-Scatter Ratio R(90%)	Albedo for Single Scatter $\tilde{w}_g$	Number of Determinations N
9. St. Louis, MO (Wash. Univ) 8-22-73/8-30-73	1.9E-4 1.2E-4 7.5E-5	0.10 0.10 0.07	0.86 0.76 0.67	50
10. New York, NY 12-14-67/ 12-22-67	7.3E-4 4.3E-4 1.3E-4	--	0.72 0.62 0.52	9*
11. Riverside, CA 11-05-75/ 11-07-75	1.1E-3 8.9E-4 7.9E-4	--	0.94 0.93 0.91	6*
Site B. Rural				
1. Milford, MI 10-1-75/10-14-75	7.1E-5 3.4E-5 1.6E-5	0.17 0.14 0.11	0.80 0.72 0.65	8*
2. Hall Mt., AR 11-6-75/12-4-75	6.2E-5 4.2E-5 2.5E-5	0.17 0.11 0.07	0.95 0.86 0.80	62
3. Pudget Island, WA 3-5-75/3-17-75	3.6E-5 1.5E-5 6.1E-6	--	0.89 0.79 0.71	23
4. Tyson, MO 9-5-73/9-26-73	1.4E-4 6.5E-5 2.9E-5	0.14 0.90 0.07	0.94 0.78 0.64	96

Table 1 Continued

Site	Scattering Extinction ± standard deviation $\sigma_{sp} \pm s_\sigma (m^{-1})$	Back-Scatter Ratio R(90°)	Albedo for Single Scatter $\tilde{w}_o$	Number of Determinations N
B. Rural				
5. Tyson, MO 8-13-75/9-26-75	1.2E-4 4.9E-5 2.1E-5	0.14 0.10 0.06	0.90 0.79 0.70	52
C. Remote, Lower Troposphere				
1. Above Flagstaff, AZ 10-30-74/11-6-74	1.9E-5 1.7E-5 1.4E-5	--	0.97 0.94 0.91	4*
2. Mesa Verde, CO 9-13-78/9-20-78	3.3E-5 1.8E-5 1.0E-5	--	0.94 0.90 0.85	4*
3. Abastumani Obs, USSR 7-4-79/7-26-79	9.9E-5 5.3E-5 2.9E-5	--	0.92 0.90 0.87	40

* No s_σ given due to small number of points. Limits are simply extremal values.
Source: Weiss, 1980 (Dissertation)

Thus, the influence of aerosol particles on radiative transfer has to include both scattering and absorption. A crude estimate of the magnitude of the effects by Bolin and Charlson (Ambio, 1976) suggested that the sulfates were dominant and that the backscatter optical depth might be in the range from 0.05 to 0.1, a quantity in rough agreement with the analysis by Ball and Robinson (JAM, 21, 1982).

More recently, questions have arisen regarding the sources, lifetime and fate of these radiatively active aerosols. Interestingly, the fate appears to be removed in rain water, which itself has significant consequences regarding composition of the rain. Besides being a dominant source of $SO_4^=$ in rain in the same area of the eastern U.S., this aerosol also provides C()) which is deposited simultaneously (Ogren and Charlson, Tellus, in press, 1984).

In the future, it is my hope to be able to study the relationships of sources, optical effects, lifetimes and fate of these same key species. It would appear to be important to understand the dependence on source strengths in order to better understand whether or how much control might be needed. Careful attention needs to be paid to the relative magnitude of natural and man-made sources. Meanwhile, some general questions for discussion at this workshop are: 1) Is the basic situation correctly

portrayed, that is, does the sulfate-dominated aerosol of the Eastern United States cause a reduction of a few to several percent in global radiation? 2) Is this loss of global radiation of sufficient magnitude to cause any observable meteorological effects besides visibility reduction (i.e. changes in temperature, static stability, cloud development, etc.)? Might there be any agricultural consequences? 3) What research is presently being done that relates to these radiative effects? What research ought to be done? 4) How well do the available papers and documents portray the nature of the influence of aerosols on radiative processes in the Eastern United States?

SOURCE CHARACTERISTICS

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Research Interests

The characterization of air pollution source emissions and associated control technology has been a long time research interest. Specifically, subjects of recent research include: fine particle formation industrial processes, the elemental nature of fine particles, modification of particle size distribution in control devices, near-stack particle formation, and plume opacity.

Present Research Projects

Our group is currently working on the following projects: opacity prediction for electrostatic precipitators, opacity of detached plumes, control of primary sulfates, control of SO_2 with dry absorption methods, mathematical modeling and fundamental studies of electrostatic precipitator and fabric filtration technology, electrostatic filtration, and aerosol instrumentation. Our plume opacity prediction research is most relevant to the present workshop, in particular with respect to effects near air pollution sources. The results of the following projects will be discussed: (1) measurement of the refractive index of fly ash and (2) visual appearance of condensing plumes.

The following properties for fourteen fly ashes from coal sources in the United States were measured: real and imaginary refractive index, particle density, and chemical composition. The real refractive index was correlated to

the concentration of the major inorganic components and the imaginary refractive index was related to carbon concentration.

A mathematical model describing the formation and growth of sulfuric acid within a few hundred meters of a stack has been developed. The model solves the differential equations describing mass, heat and momentum for the plume; and the particle formation, growth and coagulation within the plume. The light transmittance through the plume downwind of the point of emission is computed in addition to mass concentration.

Direction of Research

As atmospheric processes are better understood, detailed information about emission characteristics will be required. Specific issues include:

1. Importance of primary versus secondary emissions.
2. Alternation of the emission of fine particle by process changes implemented to control SO_2.
3. Control of primary sulfates.
4. Optical properties of primary emissions.
5. Chemical reactions in the plume near the point of emission.

ATTENUATION OF SOLAR RADIATION BY ATMOSPHERIC PARTICLES
SOME OBSERVATIONS AND CONSEQUENCES

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The first topic concerns an explanation of certain aspects of routine observatory records of direct and diffuse solar radiation at the ground on cloudless days in terms of absorption and scattering by particles in the atmosphere. This work was done between 1947 and 1955 and published in 1962. Considerable absorption was indicated. On average, Kew (London suburb) and Vienna records indicated about 20% attenuation with single scattering albedo <0.5. Median visibility was 15 km (attenuation coefficient -0.25 km^{-1}). At a remote high level station in equatorial Africa, the excess attenuation was about 7% with single scatter albedo - 0.6. These estimates of absorption met with skepticism when published, though they confirmed little-known wartime measurements.

Aircraft-mounted instruments flown sporadically by the (U.K) Meteorological Research Flight in the period 1955-1965 confirmed these general conclusions. Measurements in heavy haze indicated single scattering albedo to be about 0.5, at other times about 0.75. Albedo and absorption of cloud over southern England were measured on some of these flights. In non-precipitating cloud, the fraction of solar radiation at the cloud top which was absorbed ranged from 0.0 to 0.3.

The second topic relates to the estimation of solar irradiation at the earth's surface from commonly available standard meteorological measurements - - cloud cover, visual range, and mixing height. A standard haze model for the central USA was constructed from observed optical properties, related to

visibility and mixing height, and applied to the statistics for 25 locations. The average fractional depletion due to haze varied from 0.07 in mid-winter to 0.10 in August. Accuracy of the absolute values may be judged from Table 1. My colleagues in this work were M. A. Atwater and R. J. Ball.

The third topic is concerned with the origin and nature of the attenuating particles. The work, done in collaboration with r. J. Ball in the period 1977-1979, involved application of a rudimentary air-pollution model to the EPA 1973 emission inventories for fine particles and SO_2. Conversion between SO_2 and sulfate particles (assumed $H_2SO_4 4H_2O$) was postulated to be in accordance with an entirely empirical formula (1975 state of the art). Five occasions were examined, three characterized as heavy haze (visual range 5-10 km) two by visual range 15-25 km. Elapsed time was between 2 and 6 days. Computation and observation were in remarkably close agreement; (see Table 2) remarkable because the model allowed no fine particle fall-out and only 10% conversion of SO_2. We were unable (not for technical reasons) to extend the model to predict SO_2 concentration.

Finally the possibilities of quantitative investigation of the effects of atmospheric particles on the surface and subsurface climate are mentioned, in terms of preliminary use of a complex meteorological model --a limited area multi-layer "primitive equation" model developed by colleagues led by J.P. Pandolfo. This throws some light on the interactive secondary effects of the primary reduction in solar radiation, and on the magnitude of changes in evaporation and near-surface temperature. Initial and boundary conditions for the simulation were based on observations in Nebraska ("Great Plains" project). Optical properties of the model "light haze:" and "heavy haze" were used. As an example of the results, it was found that in the "light haze" situation the downward atmospheric radiation flux increases slightly because of the rise in

temperature of the particle-containing layer, in spite of the decrease in water content which follows the computed decrease of evaporation. In the "heavy haze" case, the downward atmospheric radiation is reduced, the effect of reduced water content outweighing that of increased air temperature.[Robinson 1] Other differences in the relative magnitude of the various components of the surface heat balance are explained in terms of the relatively high absorptive attenuation of the "light haze" and the relatively high scattering attenuation of the "heavy haze".

TABLE 1
Observed and computed solar irradiation at Nashville, TN, 1970-74, (MJ m^{-2} day^{-1}).

1 Month	2 Atwater's no haze model	3 Haze depletion factor	4 Model with haze	5 Observed
Jan	7.46	0.914	6.82	6.67
Feb	10.69	0.915	9.78	9.37
Mar	13.80	0.920	12.69	12.73
Apr	19.56	0.917	17.94	17.68
May	22.41	0.917	20.55	20.49
Jun	23.37	0.909	21.24	21.48
Jul	22.08	0.898	19.83	20.31
Aug	20.39	0.884	18.02	18.08
Sep	15.12	0.904	13.67	14.70
Oct	13.10	0.911	11.93	11.82
Nov	8.51	0.916	7.80	7.46
Dec	6.58	0.923	6.07	5.49
Year	15.26		13.94	13.86

TABLE 2
Comparison of air quality model computations with observations

Test case		Mixing height m	Computation				Observation	
			Particle concentration ($\mu g\ m^{-3}$)			Visual Range (km)	Particle concentration ($\mu g\ m^{-3}$) Total	Visual range (km)
Location	Date		Total	Primary	Sulfate			
St. Louis	10 Aug 72	840	58.1	52.3	5.8	18.2	-	16.1
St. Louis	17 Aug 72	850	147.1*	95.5	51.6	7.3	-	7.7
Des Moines	21 Jun 75	970	38.2*	27.0	11.2	28.5	-	22.9
Des Moines	29 Jun 75	700	127.9*	104.6	23.2	8.3	126	4.7
Des Moines	1 Jul 75	980	94.7	70.4	24.3	11.1	-	10.9

* Includes background contribution 20 μgm^{-3} primary 10 μgm^{-3} sulfate.

A MATHEMATICAL MODEL OF THE TRAJECTORY OF HEAVY METALS OVER THE MEDITERRANEAN SEA AND COLLECTION AND VALIDATION OF CLIMATOLOGICAL DATA IN THE PO VALLEY

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The Osservatorio Meteorologico di Brera in Milan, Italy, has been working on two major programs: (1) a program to develop a mathematical model of the trajectory of heavy metals over the Mediterranean Sea, and (2) a program to collect and validate climatological data in the Po Valley. The first program is a part of a greater international World Meteorological Organization (WMO) project to study and control pollutants over the Mediterranean Sea. In this program, we have developed a mathematical model for the trajectory of SO_2 and NO_x and are currently working on modeling the trajectories of heavy metals. (Results of this research were presented at a WMO meeting held in Athens, Greece, in the fall of 1983.)

The second program, designed to collect meteorological data from the principal observatories in the Po Valley, was established as part of a national program organized by the National Research Council. Principal results of this program to date have shown that:

(1) The temperature in the Po Valley is changing. The daily minimum temperature in the winter has increased in the larger cities such as Milan and has decreased in rural areas.

(2) The annual number of days with fog has decreased in the last 10 years. In the city of Milan it has completely disappeared, and in rural areas it appears to have decreased approximately 40 to 50 percent.

Although the major national program under which this research was conducted has been discontinued, we hope that a new research program can be started next year. This future program would study the clearance and circulation of air over the

Po Valley on urban and rural areas. Hopefully, such a program would give us a better understanding of whether these new conditions are a result of natural changes or caused by human activities. One other program the Osservatorio is planning to undertake is to study the trend of meteorological factors in the Alps during the summer season. Determining the effects on climate that are attributable to man's activities, as opposed to those attributable to natural forces, will allow us to limit more intelligently those actions of man that could be deleterious.

CLIMATIC TRENDS OVER NORTH AMERICA: POTENTIAL ROLE OF AEROSOLS

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INTRODUCTION

It has long been recognized that the amount of solar radiation reaching the surface of the earth is an important climatological variable. Abbott[1] and others demonstrated the near constancy of the amount of solar radiation reaching the outer limits of the atmosphere-as is implied by the use of the term "solar constant." Indeed, study of solar variability as a cause of climate change is still an active field of research. However, the variations in radiation reaching the surface of the earth are to a much larger extent due to fluctuations in the transmission through the atmosphere than to the variations of the solar constant itself. Aerosols, along with clouds, ozone, air and water vapor are the key factors determining the transmission.

McCormick and Ludwig[2] and Bryson[3] argued that a buildup of atmospheric aerosols could have the effect of increasing albedo, thereby cooling the earth. Charlson and Pilat[4] suggested that since particles can both absorb and scatter light, particles could either heat or cool the earth, depending on the relative amounts of absorption and scattering. Atwater[5] discussed factors governing the sign of the change in the planetary albedo caused by presence of aerosols, showing that either heating or cooling could result. Of particular importance is the albedo of the surface under an aerosol layer. Mitchell[6] also noted the roles of both scattering and absorption, with similar conclusions depending on albedo, but with some adjustment for evaporation of water at the surface. Ensor et al.[7] developed a model that allowed the imaginary refraction index to be varied, concluding that large ambiguities exist due to a lack of data on the absorption and scattering properties of aerosols. Reck[8-10] explored a variety of the parameters that are imbedded in models of the influ-

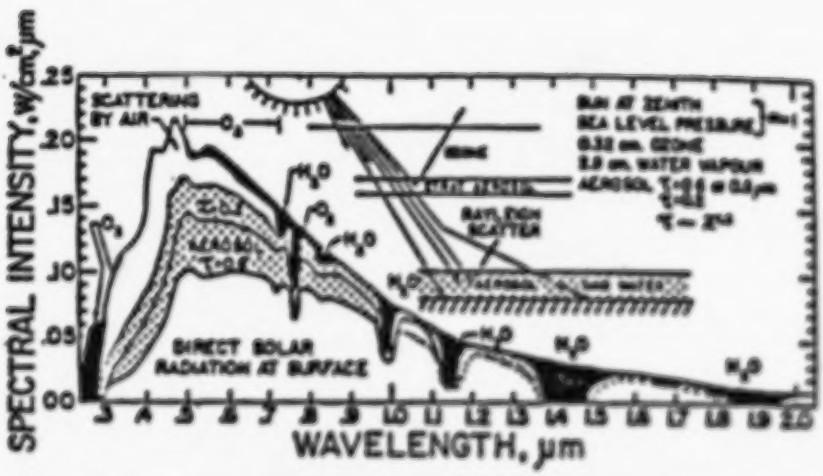

Figure 1. Illustration of solar radiation spectrum outside the atmosphere and depleted by ozone, water vapor, Rayleigh scattering and aerosol. Parts adapted from Bowles and Dave.[5]

ence of aerosols, suggesting that aerosols cool the atmosphere, reduce convection and increase planetary albedo.

Aerosols also have an influence on the optical properties and microphysics of clouds. Increases in pollution aerosol lead to increase in the number of cloud condensation nuclei resulting in an increased albedo. Carbon particles are present in rain, snow, and ice, and are therefore expected to be in cloud droplets. The presence of carbon should lead to a decrease in albedo. Hobbs et al.[11] suggested that pollutants affecting clouds are the most likely to produce modifications in weather and climate.

Robinson,[12] Robinson et al.,[13] and Ball and Robinson[14] discussed in general the effects of the particulate matter associated with energy production, focusing on surface temperature, planetary albedo and atmospheric heating. A major conclusion was that energy production, e.g., from burning sulfur-containing coal, resulted in a net energy loss from the earth's surface. That is, more solar energy is absorbed in the atmosphere and reflected into space than is released by the burning of coal.

TRANSMISSION OF SOLAR RADIATION

In an aerosol-free atmosphere, about one third of the solar energy passing through a zenith angle of 60° (about 2 air masses) is depleted by Rayleigh scattering, water vapor and ozone absorption even in the absence of scattering and absorbing particles. On the order of 10% of the lost direct radiation is recovered as blue skylight, while another 10% is backscattered to space to give the earth's atmospheric shell its bluish color as viewed from space. The remaining depleted energy heats the stratospheric ozone layer and the near surface layer containing the water vapor.

The scattering, ozone and water vapor absorption processes act on different parts of the solar spectrum as shown schematically in Figure 1. Furthermore, the atmospheric areas containing the ozone, air and water vapor are also separated. The incoming solar photons first encounter the ozone layer at 10-40 km above sea level. High energy photons in the UV ($\lambda < 0.30$ μm) are absorbed in the strongly absorbing bands which, however, saturate quickly with increasing ozone depth. The absorption in the visible band, on the other hand, continues to increase almost linearly with ozone depth.

The second chance for the photon-atmosphere encounter occurs when the solar photons pass through the bulk of the atmosphere. Molecular scattering changes the photon direction mostly in the blue end of the spectrum since the scattering is $\sim \lambda^{-4}$.

A third kind of encounter occurs when the solar photons reach the lowest layers of the atmo-

sphere where most of the water vapor is contained. Water is a major "source" of atmospheric heating via its selective absorption of solar photons in the near IR bands. For water paths > 2 cm of precipitable water the increase in amount of solar radiation absorbed is markedly reduced due to the saturation of the main absorption bands.

Typical winter values of precipitable water amounts of the atmosphere are 0.5–1.0 cm in a vertical column over the eastern U.S.; in the summer it ranges between 2 and 4 cm.

The presence of aerosols in the mixing layer leads to a number of perturbations in the radiative energy balance. The aerosol layer over the eastern United States may cause, on a yearly average, a loss of about 7% of the solar energy which would otherwise reach the ground. About one-half is lost by backscatter to space. The other half is absorbed within the boundary layer with the heating of the ground and more heating of the air in the boundary layer. How the through emissions of long wavelength radiation by aerosols may or may not balance energy absorptions in the visible wavelengths. If one process dominates the other, the aerosol may lead to either net cooling or a net heating of the boundary layer.

TURBIDITY

In the absence of clouds, the intensity of direct solar radiation for a given solar elevation depends on the variable amount of dust, haze, and water vapor in the atmosphere. The extinction produced by these constituents is called "atmospheric turbidity." During hazy episodes, turbidity coefficients as high as 0.4 or 1.0 have been reported, considering zero a 10 or 40% removal of solar radiation from the direct beam, a 1.0 or 9% loss to space, and 1.0 or 9% loss to atmospheric heating.

Data from a 28-station turbidity network showed that there are strong spatial and temporal variations of turbidity across the United States. At all sites, the highest turbidity occurs in the summertime and the lowest occurs in the winter, which is consistent with the haziness pattern observed from visibility observations. The turbidity of the atmosphere in the United States has a strong spatial dependence. In the Southwest, with a mean annual turbidity coefficient of about 0.08, the incoming direct solar radiation is decreased by only 10%, compared with Midwest values of about 20%.

The highest turbidity coefficients were observed in the Eastern United States (Figure 7) where winter values of 0.1 and summer values of 0.2 were typical, meaning loss about 20 to 40% of the direct solar beam is diverted or dry light, backscattered to space, or absorbed.

In the 1970's, the U.S. turbidity network was expanded under the auspices of the World Meteorological Organization (WMO). In the northern hemisphere there were about 100 operating stations. As with every network, the quality and quantity of data from individual stations are highly variable. The global turbidity network has been deteriorating since 1970, and it is not certain whether it will survive the decade of the 1980's.

TRENDS OF REGIONAL CLIMATE OVER EASTERN U.S.

This work presents the statistical web trends for climatic parameters that are commonly influenced by atmospheric haze and soot veils. The goal was to explore whether any significant regional climatic changes had occurred in the 1950-80 period.

The analysis here spans a 40-year data base of 1-hourly surface meteorological observations for about 200 stations covering the U.S. and Canada. The data base utilizes computerized station records compiled by the NOAA National Climatic Center and by the Atmospheric Environment Service Canada. In other letters, the climatic changes will be discussed for the warm seasons (May, August, September). This season shows the most significant trends in haziness.

The computed web maps of land-wave surface temperature are shown in Figure 1. It is evident that since the 1950's there has been a reduction of web-day temperature and a web-pronounced rise in the northeastern part of the U.S.

Figure 2 depicts the average temperature difference between warm and midnight observations, it shows a reduction of the daily temperature oscillations - the more midnight observations is the rise in the 1970's than in the 1950's.

A climatological map of stations U.S. web temperature is shown for the nine periods 1946–70 and 1970–79 in Figure 3.

The yearly trend of the summer season, 1946 to temperature for a typical locality (Evansville, Indiana, Daytona, FL), is shown in Figure 4 along with the temperature trend of the seasons maximum.

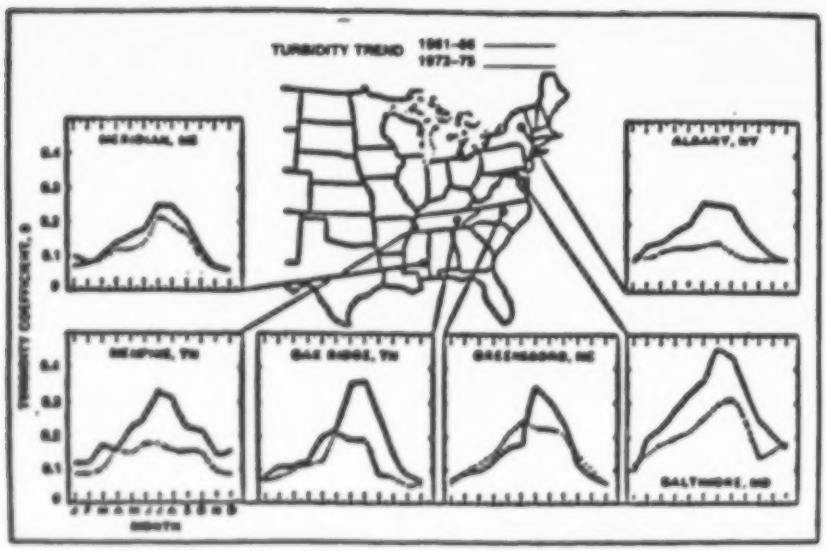

Figure 2. Seasonal turbidity patterns for 1961–1966 and 1973–1975 are shown for selected regions in the Eastern United States.

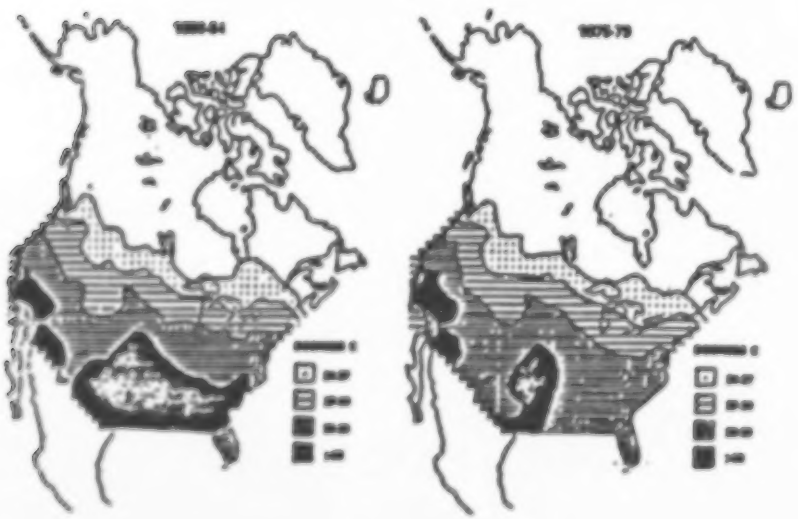

Figure 3. Mean temperature contour maps. Summer averages (3rd quarter).

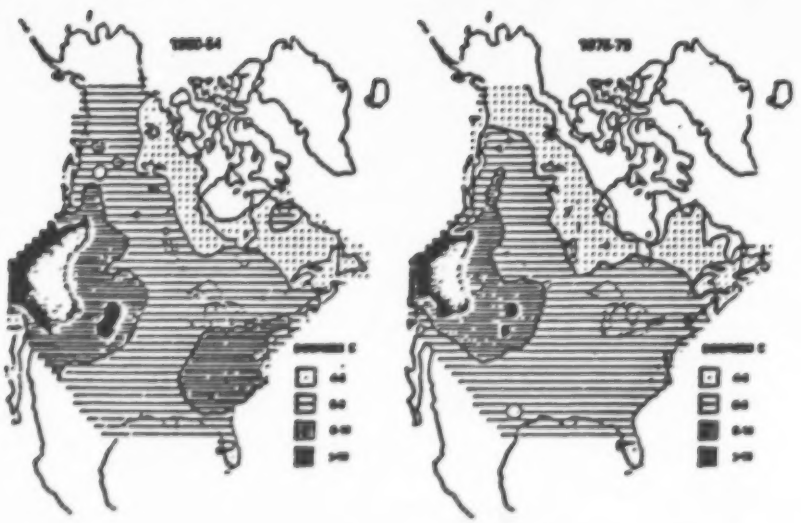

Figure 4. The average differences between noon and midnight temperatures. Summer season (3rd quarter).

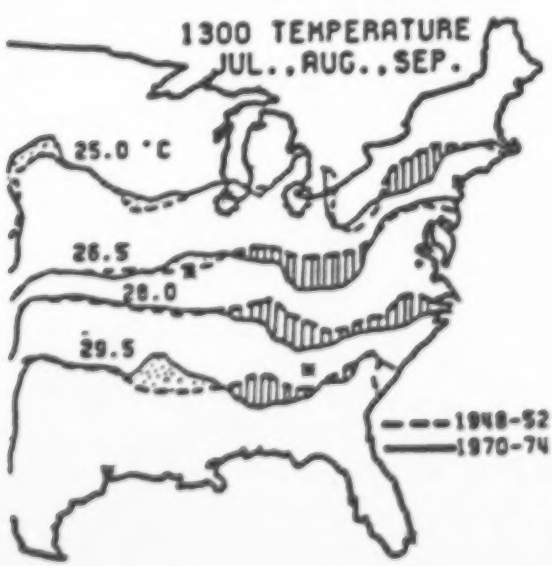

Figure 5. In the midwestern and east coast regions, the noon temperature contours for 1948–52 and 1970–74 match closely. In the east central U.S. and central New York state, however, the contours shifted southward by 100–200 km, indicating noon cooling (shaded area). The dotted regions represent warming.

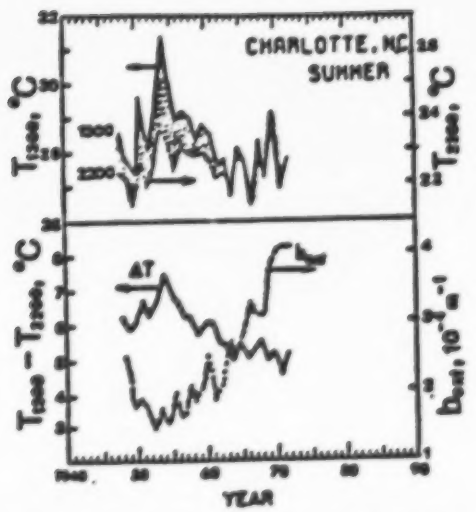

Figure 6. In the 1950's, the noon temperature was about 6.5°C higher than the 2200 temperature. By the 1970's, the diurnal temperature pattern was demodulated such that the corresponding temperature difference was only 5°C.

The most remarkable 30-year climatic change is noted for dew point (Figure 7). In the 1950's only a narrow belt of the Gulf coast recorded noon average dew point in excess of 20°C. By the 1970's this high dew point belt had expanded several hundred kilometers inland from the Gulf Coast. For the entire eastern U.S. average this resulted in a dew point increase from 16.7 to 18°C. Here again it is worth emphasizing that neither the western U.S. or Canada exhibits such trends. It is thus not likely that experimental or data processing errors are responsible for the trends.

The observed reduction of the noon temperature coupled with an increase of dew point resulted in a substantial increase in noon average relative humidity (Figure 8). In the 1950's virtually the entire U.S. had a noon average RH below 55%. By the 1970's the entire eastern U.S. exceeded this RH. Thus, on the average, the eastern U.S. noon RH has increased from 54.6 to 60.5%.

Secular trends are presented here for two measures of cloud cover (Figures 9 and 10). The noon cloud cover reported by the U.S. weather stations refers to the percent of the sky covered by clouds within the lowest 1–2 km of the atmosphere. Canadian surface observations do not contain this parameter causing a sharp gradient at the U.S.–Canadian border (Figure 9). The noon low level cloud cover east of the Mississippi was 31% and increased to 35% by the 1970's. The increase was again most pronounced in the southeastern states.

The maps of the north American noontime total sky cover are depicted in Figure 10. The pattern shows an increase from 58 to 63% for the eastern U.S.

The estimation of the low level and total cloud cover is made subjectively by individual observers. It is thus conceivable that an increased haziness of the sky prompted observers to overestimate the sky cover in the 1970's. On the other hand, the increased cloud cover is consistent with the measured increase of atmospheric moisture over the southeastern U.S. If, in fact, the eastern U.S. cloud cover has increased by 5% over the past 30 years, it could explain both the temperature reduction and demodulation.

The observation of fog is again a subjective judgment made by the observers. It generally refers to visual range less than 0.5–1 km. The North American map of reported fog frequencies shows that in the 1950's only the New England states, Quebec and Nova Scotia have experienced fog more than 10% of the time. By the 1970's virtually the entire eastern North America had experienced fog more than 10% of the time. The eastern U.S. average fog frequency had doubled from 7% to 14% of the 3-hourly observations (Figure 11).

The precipitation frequency is mapped in Figure 12. It is evident that the rainiest regions are in

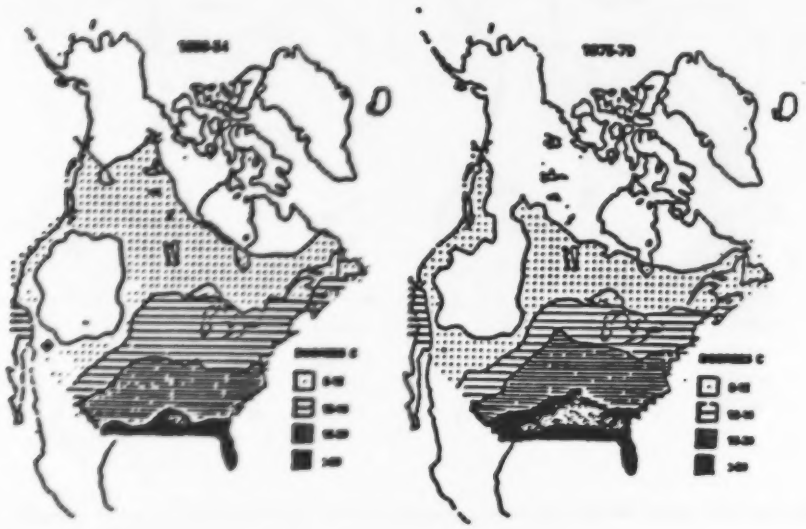

Figure 7. Noon average dew point in °C. Summer season (3rd quarter).

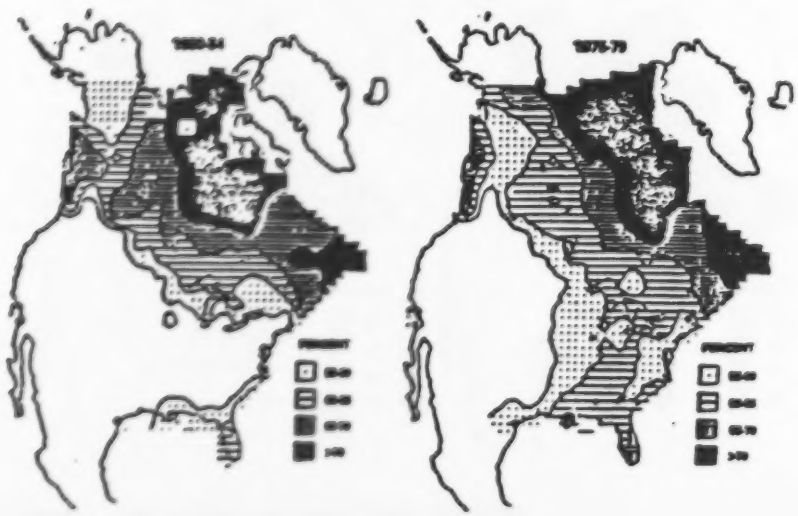

Figure 8. Average relative humidity. Summer season (3rd quarter).

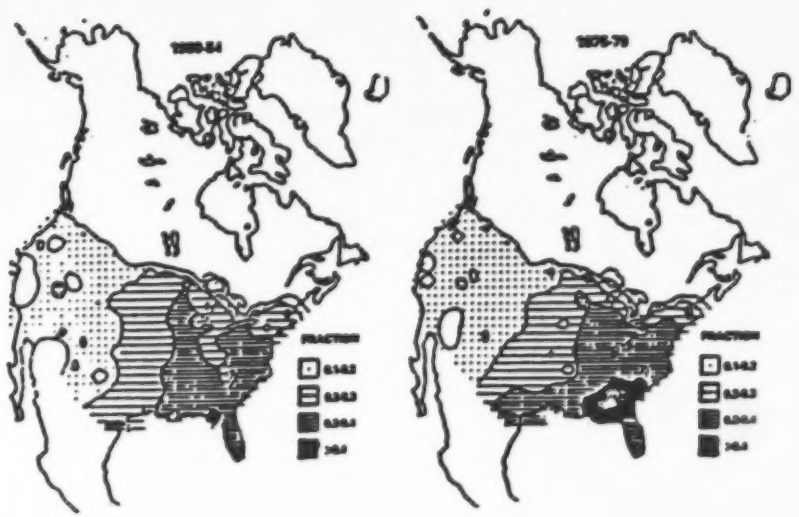

Figure 9. Noon low level cloud cover. Summer season. Low level cloud data for Canada is not available (3rd quarter).

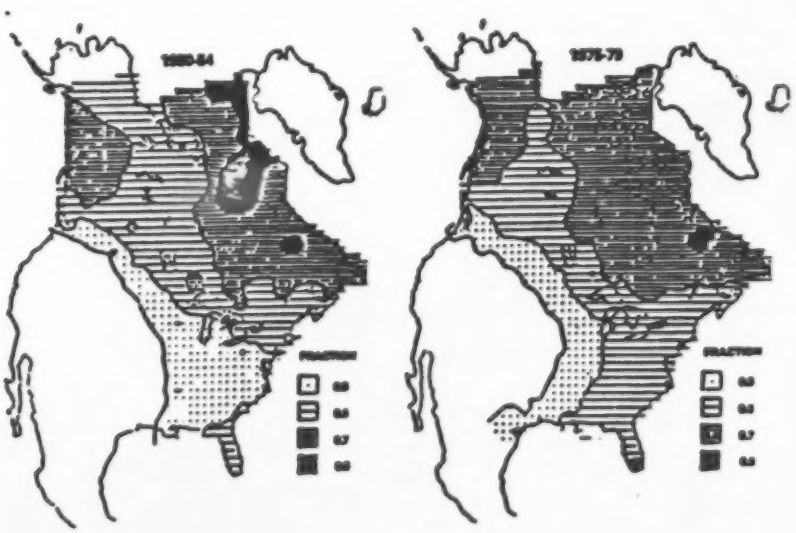

Figure 10. Noon total cloud cover. Summer season (3rd quarter).

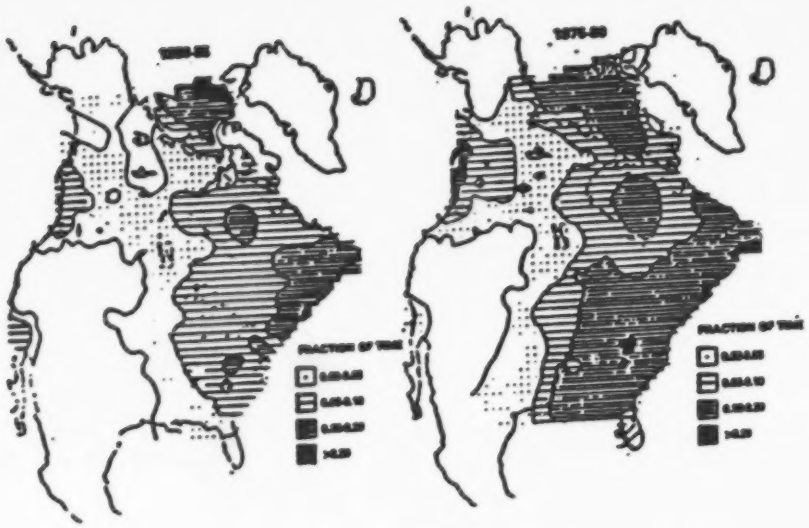

Figure 11. Fog observations for summer seasons (3rd quarter).

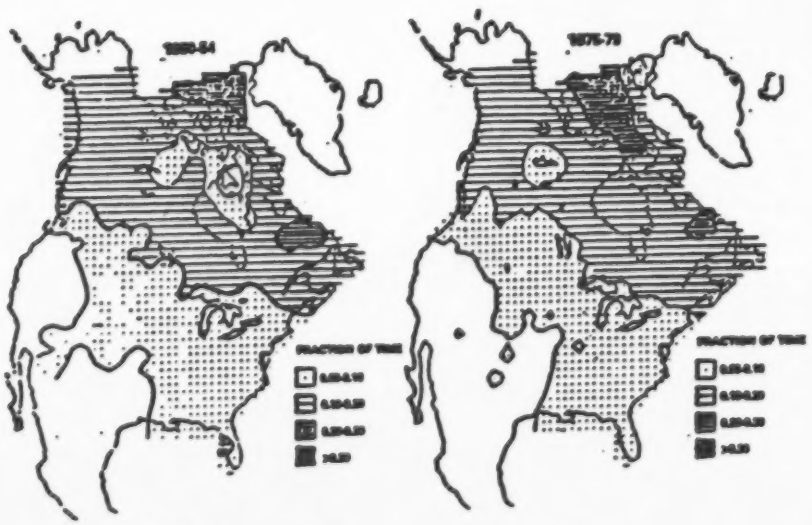

Figure 12. Fraction of time with precipitation for summer season (3rd quarter).

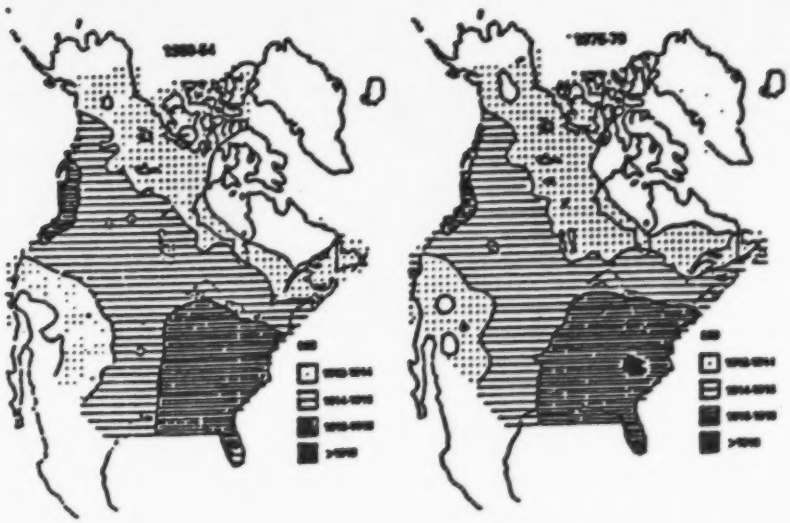

Figure 13. Noon sea level pressure field for summer season (3rd quarter).

Canada (>20% of the time), while the least rainy is the arid southwest (<5% of the time). The eastern U.S. raininess does not show a significant secular trend.

A potential cause of secular climatic trends is a change in the regional scale circulation pattern. Currently we do not possess a convenient measure of the regional moisture and heat transport field. A possible surrogate for this purpose is the sea level pressure field depicted in Figure 13. The main features of the North American pressure field were similar in the 1950's and 1970's, although there was a slight increase of the eastern U.S. average from 1016.7 to 1017.3 mb. It is unclear whether this magnitude of pressure change might be responsible for the observed temperature, moisture and cloud cover trends.

The increase in turbidity observed during the decades 1960 and 1970 is paralleled by an increase in haziness as indicated by human observer measurement of visibility distance at airport weather stations. Increases in relative humidity caused aerosol particles to increase in size increasing the light scattering. Thus the increase in turbidity and haziness could be attributed to the increase in relative humidity. It is possible to adjust the light scattering, inferred from visibility distance measurements, to a standard relative humidity. When the scattering is corrected to 50% RH as shown in Figure 14 (Husar et al.,[17] there is clearly an increase in total fine particle loading. Therefore, it seems reasonable to look for mechanisms by which an increase in fine particle pollution could lead to the observed changes.

SUMMARY AND CONCLUSIONS

To summarize the findings, comparisons on data from 1950–54 and 1975–79 indicate a reduction in eastern U.S. noon surface temperature of over 1°C (no change in western U.S. and Canada) and an increase in midnight temperature. The areas of climatic change coincide with the area of increased aerosols in the atmosphere. Also, there have been changes in the dew point from 16.7 °C to 18.0 °C and an increase in relative humidity from 54.5% to 60.5% for the eastern U.S. During the same period, there has been an increase in cloud cover in the lower layer of the atmosphere (the same layer where haze occurs) of 30% to 35%. Fog frequency doubled from 7% to 14%, and total noontime cover increased about 5%, from 58% to 63%. Though there was no observable change in frequency of precipitation, there was some increase in the summertime pressure field, thus bringing in more moisture. In sum, there is a consistent data base showing climatic changes in the eastern U.S. These climatic changes correspond in space and time to

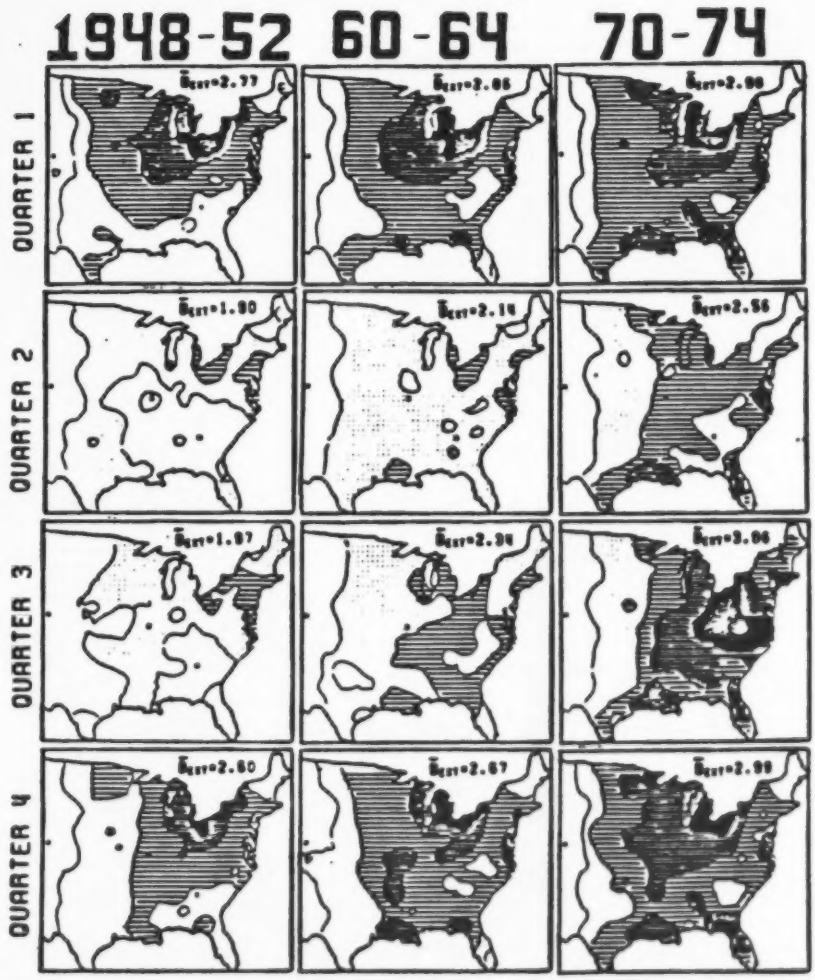

Figure 14. The spatial distribution of five-year average extinction coefficients show the drastic increases of quarter 3 extinction coefficients in the Carolinas, Ohio River Valley, and Tennessee-Kentucky area. In the summers of 1948-1952, a 1000 km size multistate region centered around Atlanta, Georgia, had visibility greater than 15 mi, which has declined to less than 8 mi by the 1970's. The spatial trend of winter (quarter 1) visibility shows improvements in the n.E. megalopolis region and some worsening in the sunbelt region. Both spring and fall quarters exhibit moderate but detectable increase over the entire eastern U.S.

increased haziness. The challenge is to justify scientifically the attribution of these climatic changes to the increase in the amount of haze in the region.

In the course of this work, although not presented here, we have examined the trends of several other meteorological parameters such as the demodulation of the diurnal RH changes, regional shifts in the RH and temperature distribution functions, etc. and they were consistent with the demodulation of the daily temperature fluctuations. We are also aware of works which state that

an increase in aerosol loading could change the regional microclimate (e.g. Robinson et al.,[13] or global atmospheric temperature (e.g. Bolin and Charlson,[15]). Angell and Korshover[19] also reported substantial decreases in the total hours of solar radiation over the southeastern U.S., which could be due to "delaying sunrise" and "advancing sunset" (from the point of view of an on-off solar radiation detector). We are also aware of the fact that most of these observed anomalies could be due to an increase of daytime cloudiness, which may or may not be related to human activities. The robust nature of the planetary atmosphere, with its numerous apparent and hidden feedback mechanisms, also provides a warning. Hence, prudence dictates that with our current experience and capability we do not claim any conclusion as to whether the observed climatological changes over the east central U.S. are primarily due to an increase in anthropogenic haziness. Nevertheless, these trends contribute to the appeal of the genesis strategy (Schneider[20]).

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INTERACTIONS BETWEEN ATMOSPHERIC AIR QUALITY AND FOREST VEGETATION

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My major area of research interest is the development of models to predict energy and mass exchange between vegetated surfaces and the atmosphere, and the collection of experimental data to test these models. This area of research effort was initiated in the early 1970's and has resulted in a fairly complex micrometeorological model as well as several simplified versions. The models have been used for estimating vegetation photosynthesis and evaportranspiration, as well as the uptake of SO_2 by vegetation. As our understanding of particle deposition improves, they also have the potential for estimating dry deposition.

My experimental field measurements include an extensive data set to test the micrometeorological model under forest conditions, as well as to obtain direct measurements of forest photosynthesis and evapotranspiration. Using micrometeorological methods we have also estimated hydrocarbon fluxes (terpenes) from forest vegetation. Most recently we have become involved in investigating the capacity of vegetation to serve as sinks for dry deposition. Our initial effort was concerned with evaluating various surrogate surface techniques for dry deposition estimates of sulfate. Currently we are initiating a study to obtain reliable estimates of dry deposition on forest foliage surfaces.

Another, quite intensive and recent study is concerned with the measurement of the characteristics of turbulent air flow within tall (forest) vegetation. None of the present models for atmospheric turbulent exchange adequately describe the turbulent exchange processes within the canopies of tall vegetation and between them and the atmosphere. Thus we are currently making intensive

measurements of turbulent exchange within a forest canopy using sonic anemometry. We will use these measurements to develop a better description of the characteristics of canopy turbulence and to propose alternative models for this exchange process. An ultimate application of an improved understanding of canopy turbulence will be to make better predictions of dry deposition to forest vegetation.

I believe the major contribution I can make to this workshop is to provide some perspective on the potential impact of decreased solar radiation (from atmospheric haze) on biological productivity. One of my major interests in modeling and measuring processes of the physical environment is to provide this information as inputs to models for biological productivity. While solar radiation is related to biological productivity, this relationship is complex. Photosynthesis in some plants becomes light saturated below maximum levels of solar radiation. For these species some reduction in solar radiation may have essentially no impact on primary production. Both photosynthesis and respiration, the net balance of which determines primary production, are also temperature dependent. Thus, there is an indirect effect of changes in solar radiation on primary production through changes in ambient temperatures. Primary productivity is also dependent upon an adequate supply of soil moisture. Thus potential changes in primary production, resulting from changes in solar radiation, may be either enhanced or counteracted if there are associated changes in the regional climatic patterns of precipitation and temperature. Finally, changes in solar radiation may have insignificant effect on sites where nutrient limitations restrict biological productivity.

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